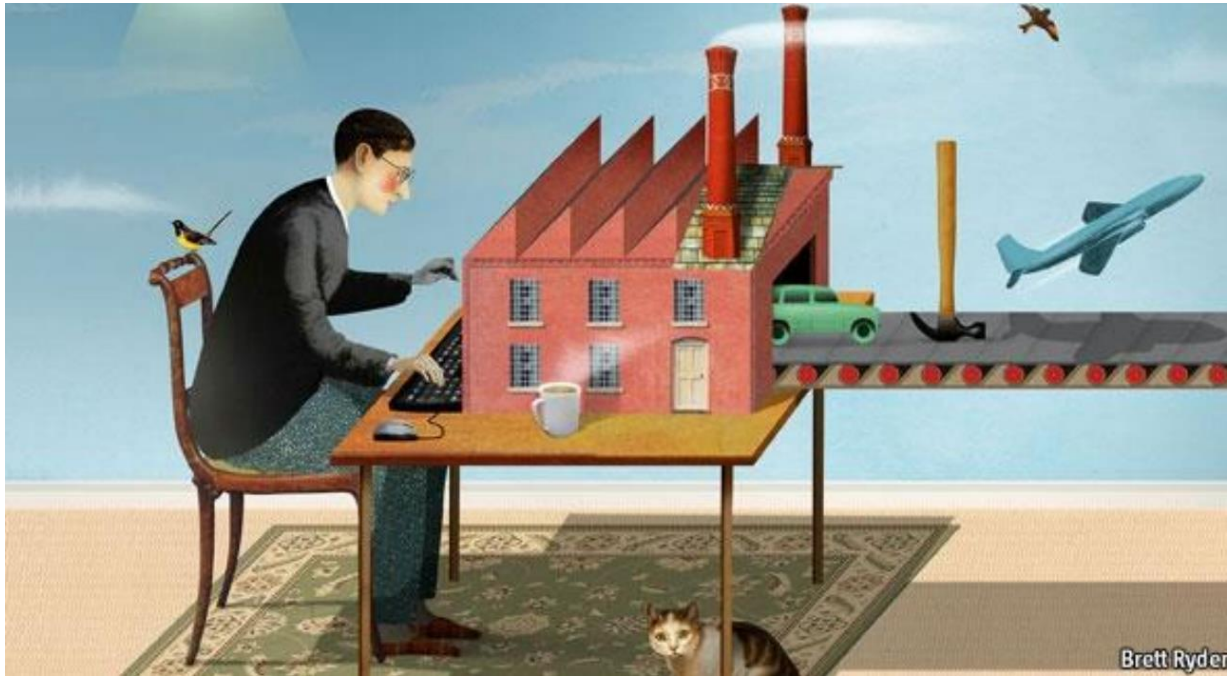
Introduction to Computational Fabrication



Amit H. Bermano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The manufacturing technology that will change the world
This violin was made using an EOS laser-sintering 3D printer (and it plays beautifully)


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Konkurrenz für Google Maps
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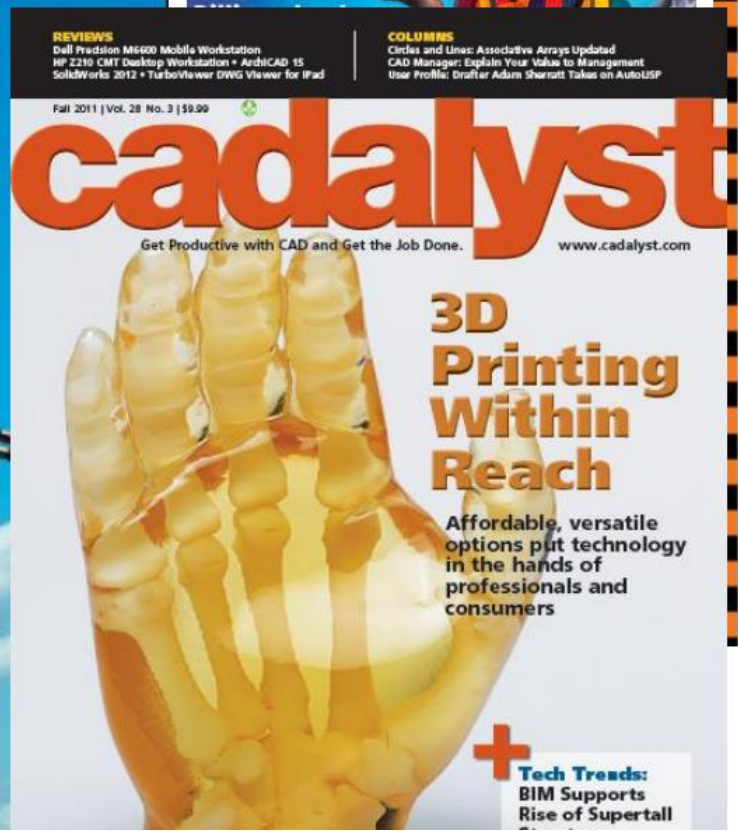
55 Alternativtinten im Test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MAKE BELIEVE | OCT 2012
THIS MACHINE WILL CHANGE THE WORLD
This man [MAKERBOT'S BRE PETTIS] will show you how.
Print amazing objects at home!
THE NEW REPLICATOR 3-D PRINTER

Additive Manufacturing

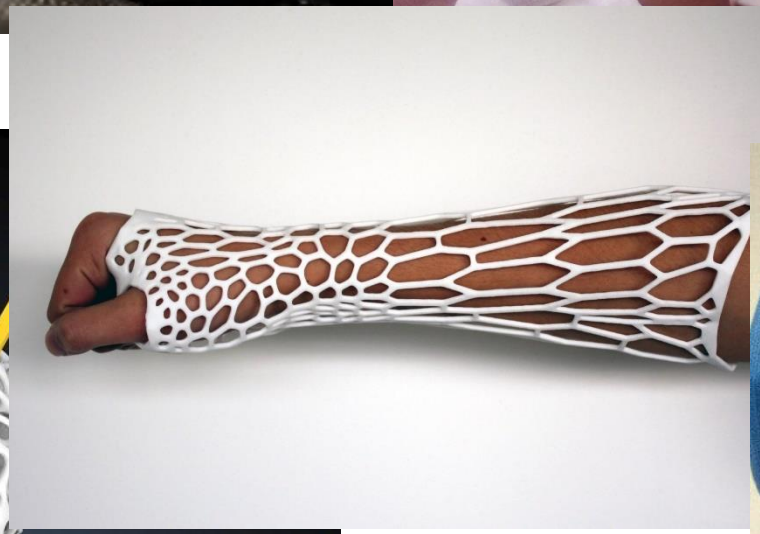
$7B ⟶ $640B

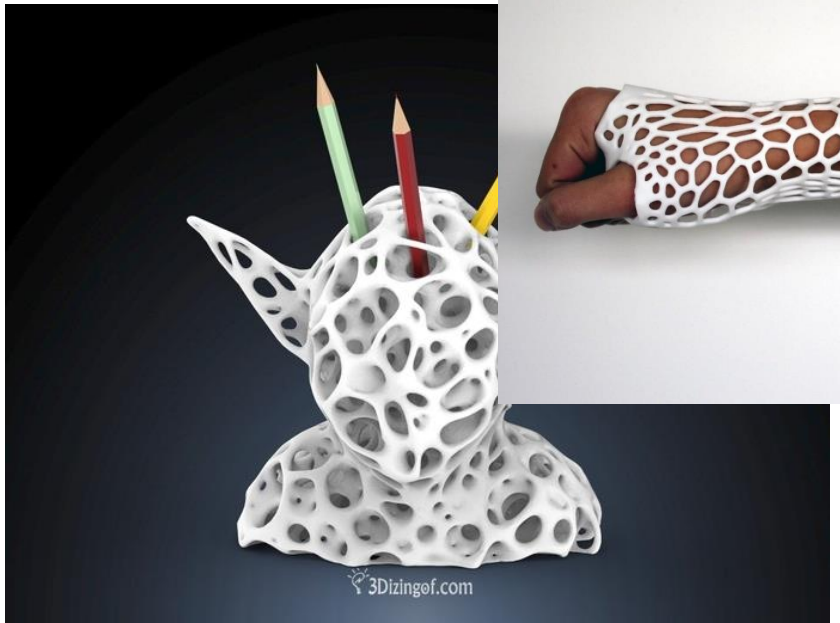
Global manufacturing Market:

0.04% ⟶ 5%

The Third Industrial Revolution

The Third Industrial Revolution



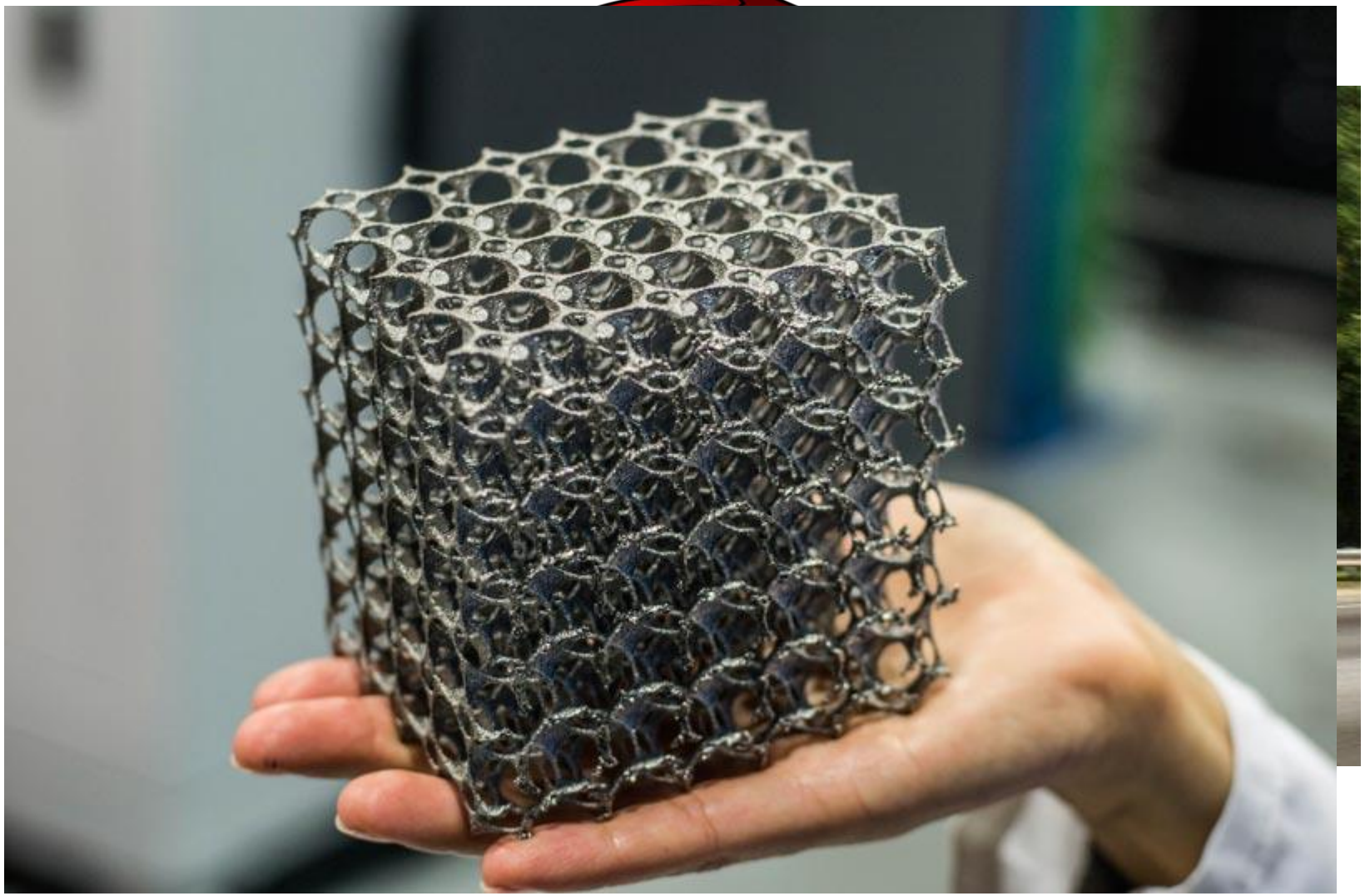


The Third Industrial Revolution

Material waste

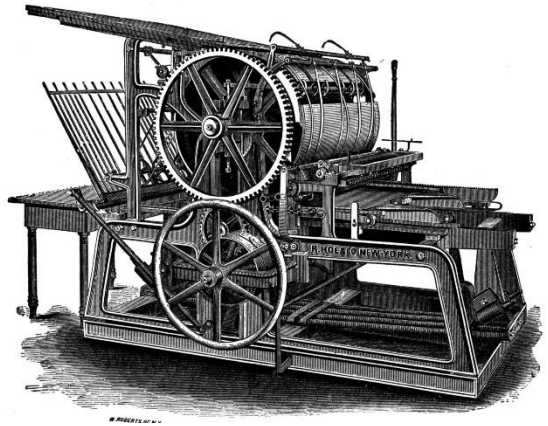
Shipping costs

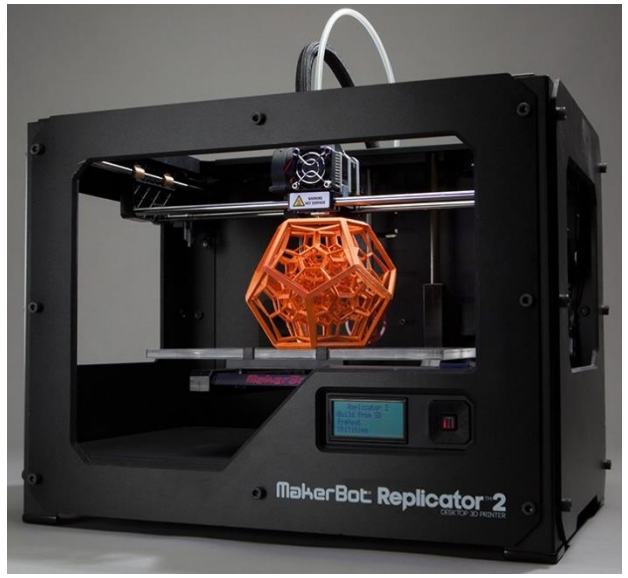
Complexity



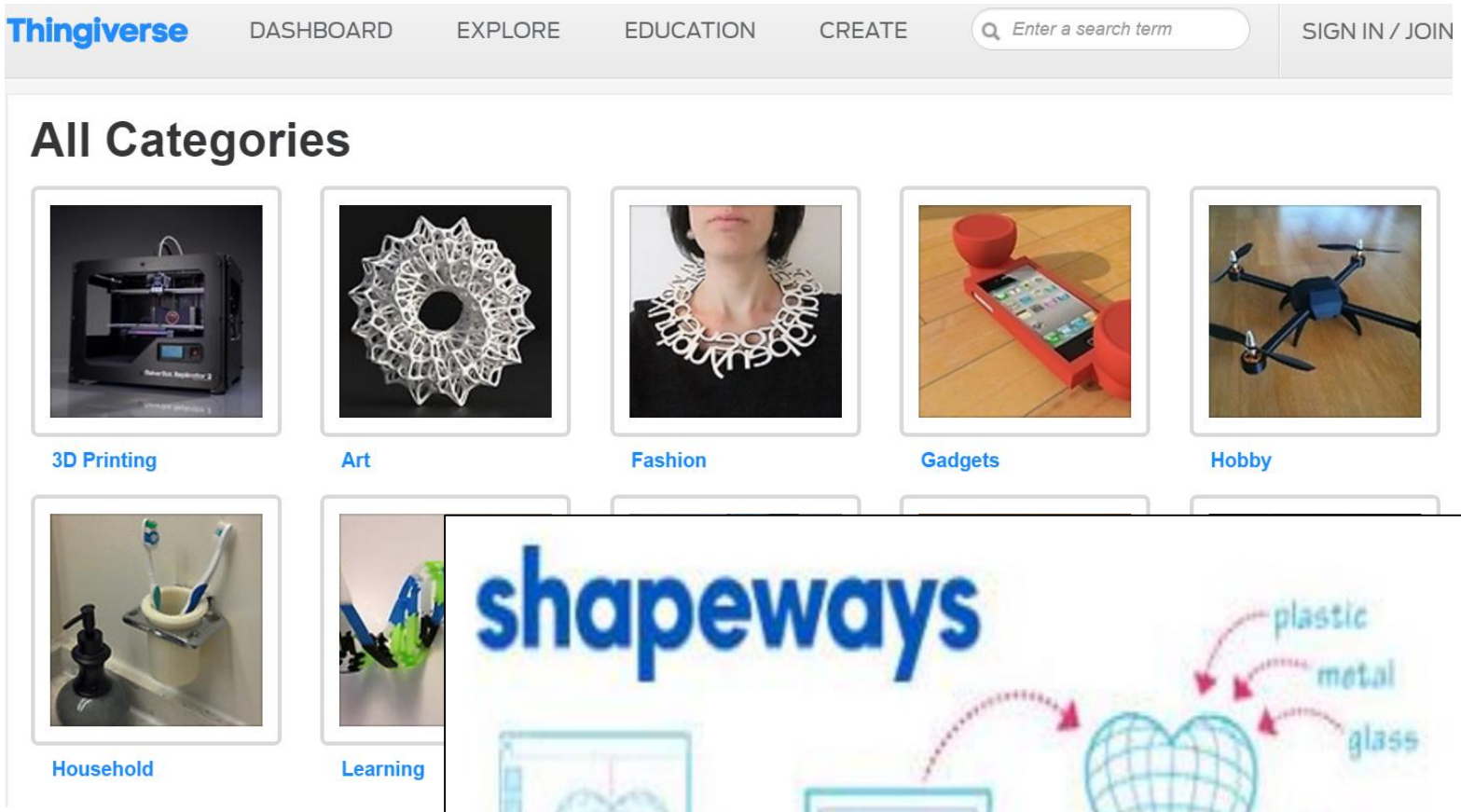
https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-tooling.html

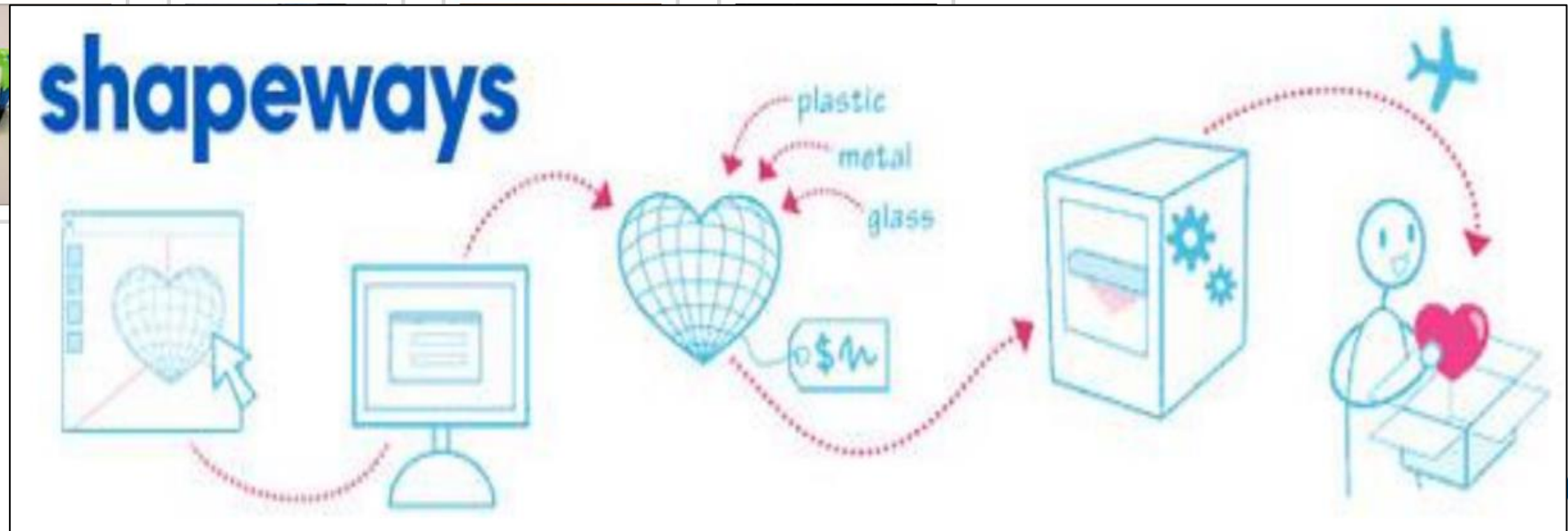
The Third Industrial Revolution





The Third Industrial Revolution





Agenda

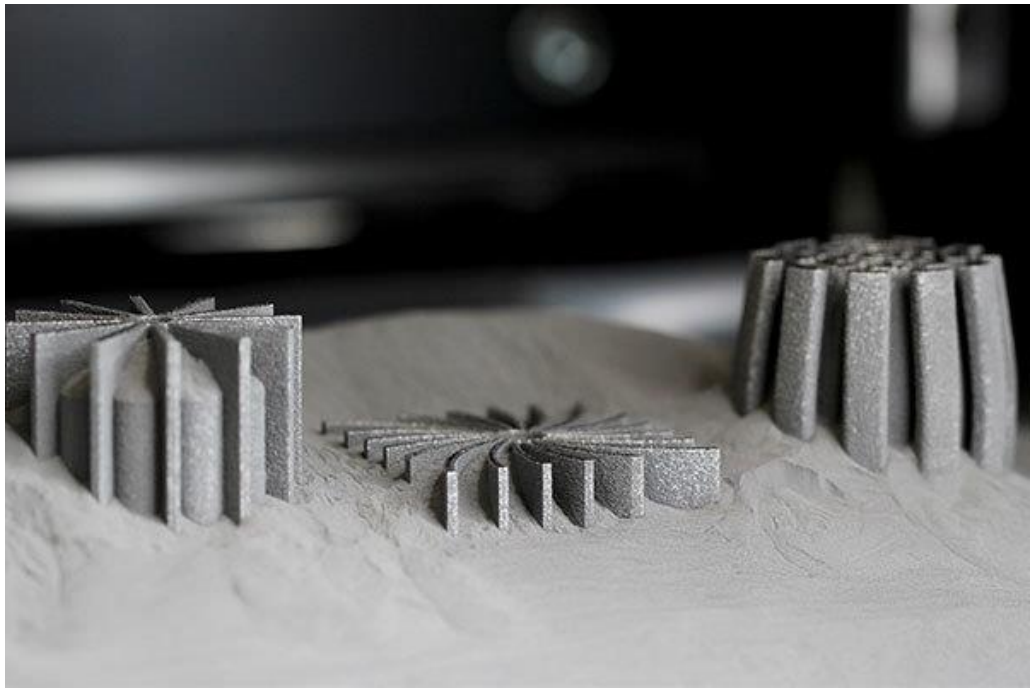
- What is additive manufacturing?
- Challenges
- Computational fabrication and graphics?
- Computational fabrication in graphics

Agenda

- **What is additive manufacturing?**
  - **Technologies**
  - **Applications**
- Challenges
- Computational fabrication and graphics?
- Computational fabrication in graphics

Additive Manufacturing

- Additive vs. Subtractive
  - Most of current manufacturing is subtractive
- “3D Printing” coined at MIT in 1995



Additive Manufacturing Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- Digital Light Projector (DLP) 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

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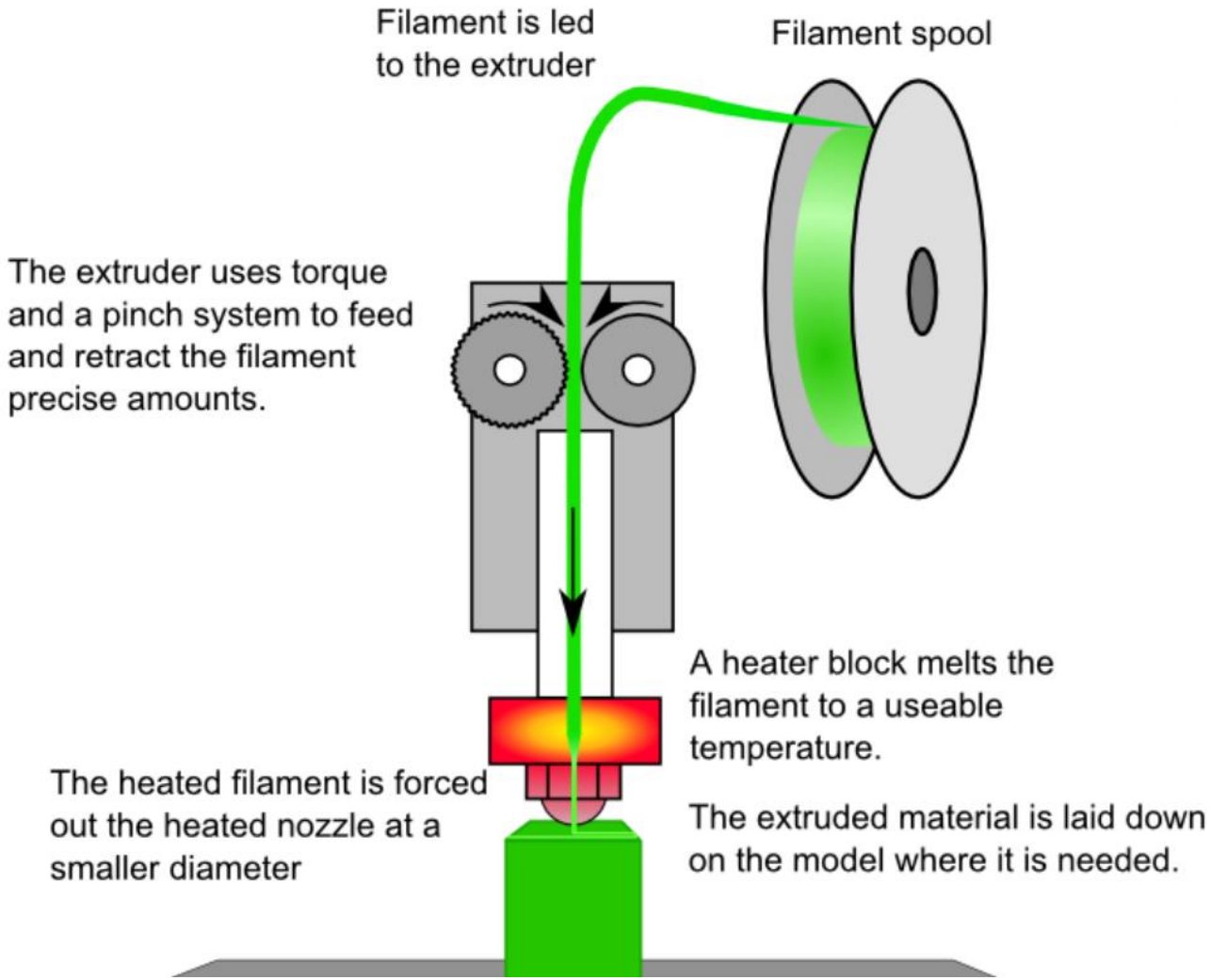
Fused deposition modeling (FDM)



Fused deposition modeling (FDM)

Fused deposition modeling (FDM)

OBJET Connex
$250K

MakerBot Replicator 2
~$2K

More units sold per month
than OBJET Connex ever

Additive Manufacturing Technologies

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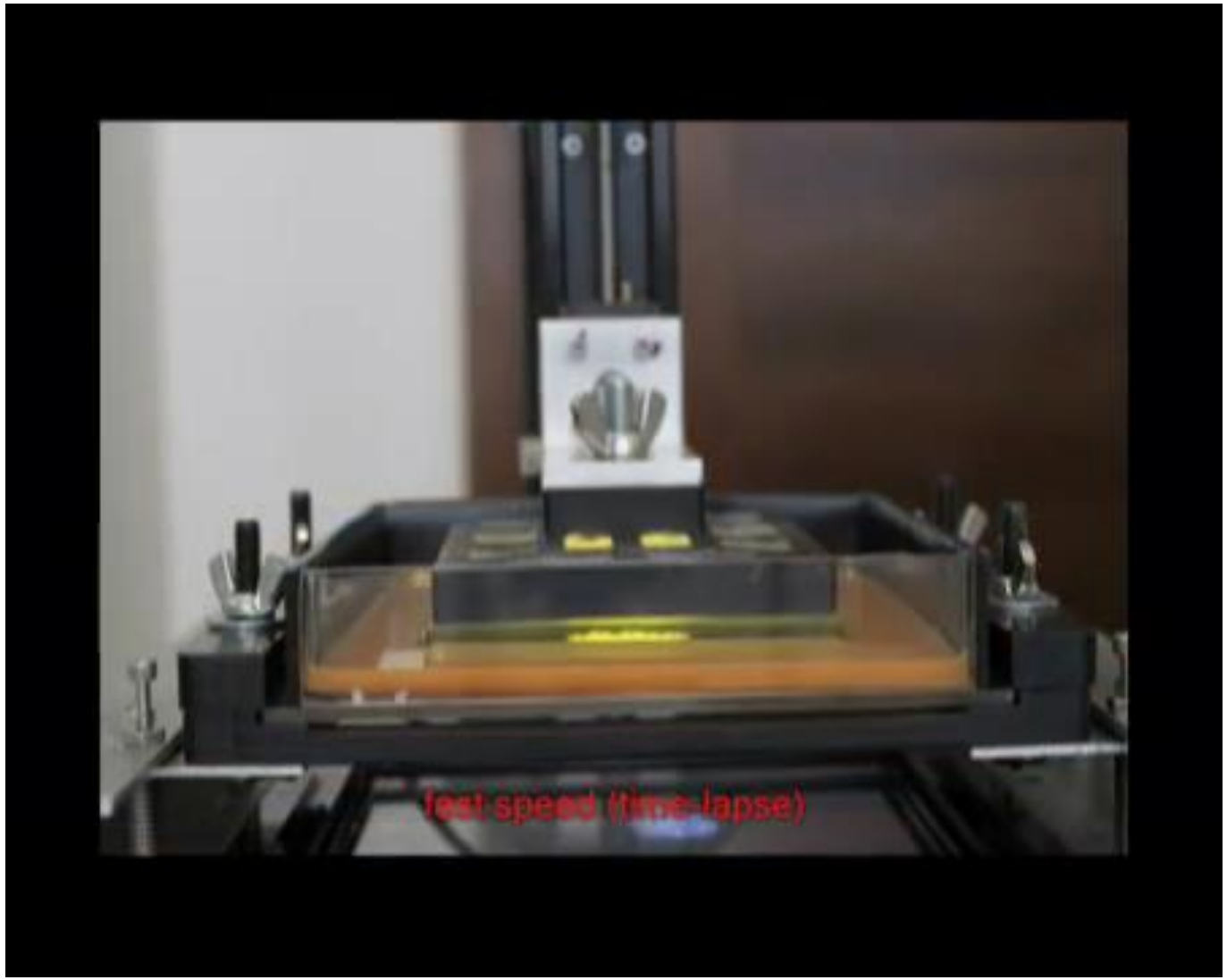
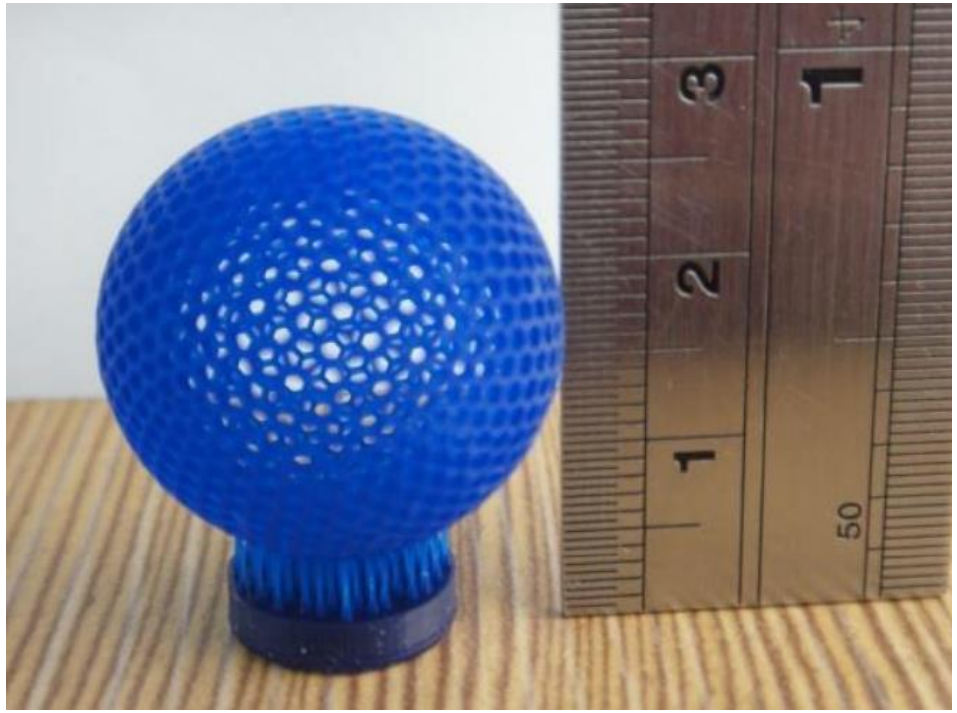
Stereolithography (SLA) & DLP



Stereolithography (SLA) & DLP



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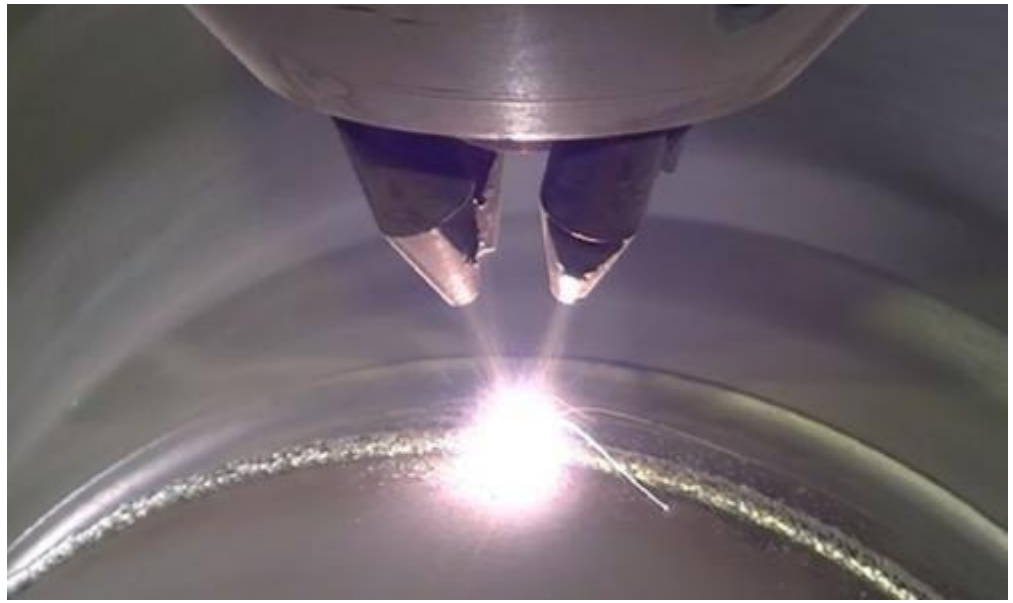
Laser Sintering



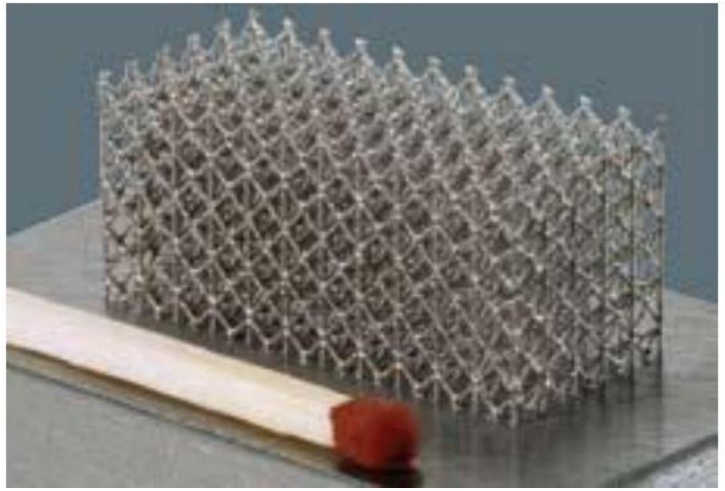
Laser Sintering

Consumer Level SLS

Consumer Level SLS

https://www.youtube.com/watch?time_continue=4&v=Q8al0846stk

Laser Sintering



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Plaster-based 3D printing (PP)

Plaster-based 3D printing (PP)

Additive Manufacturing Technologies

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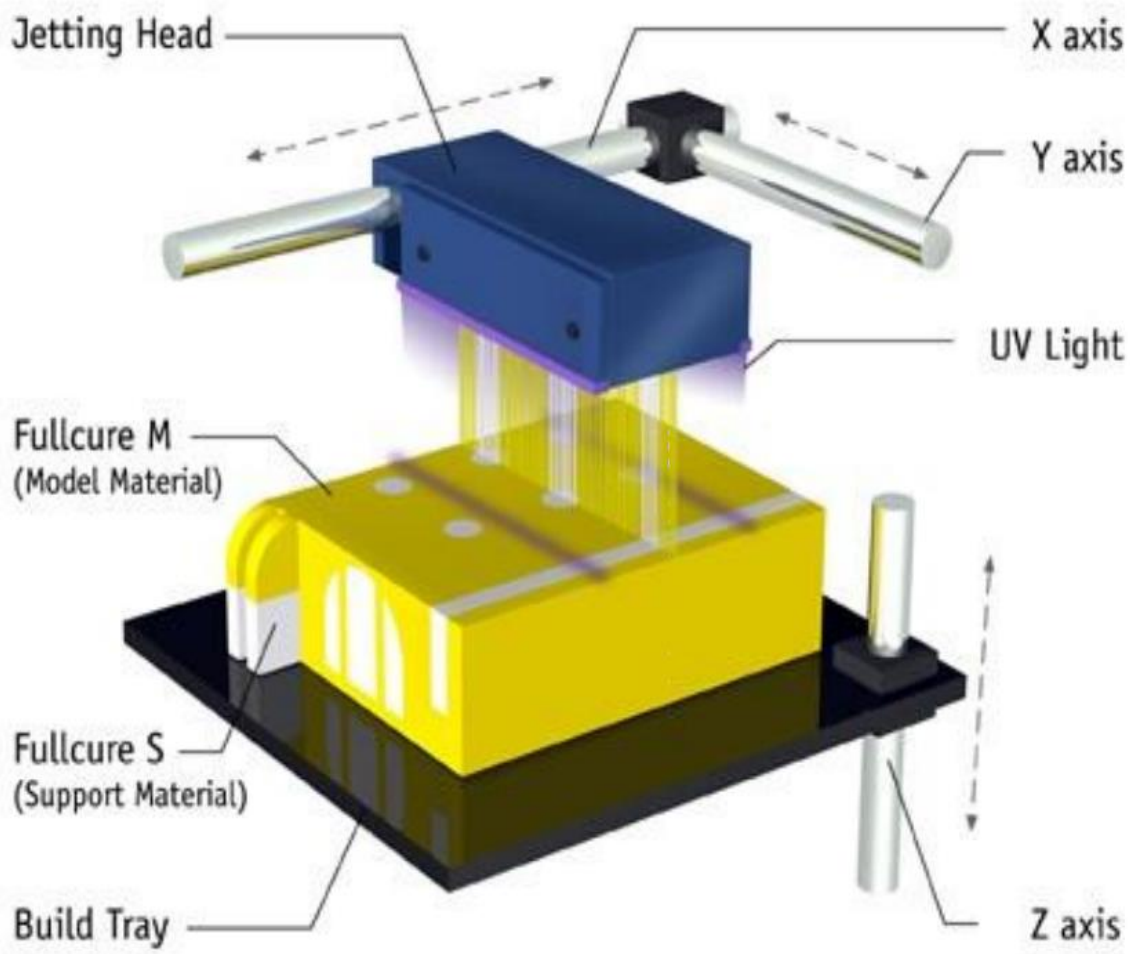
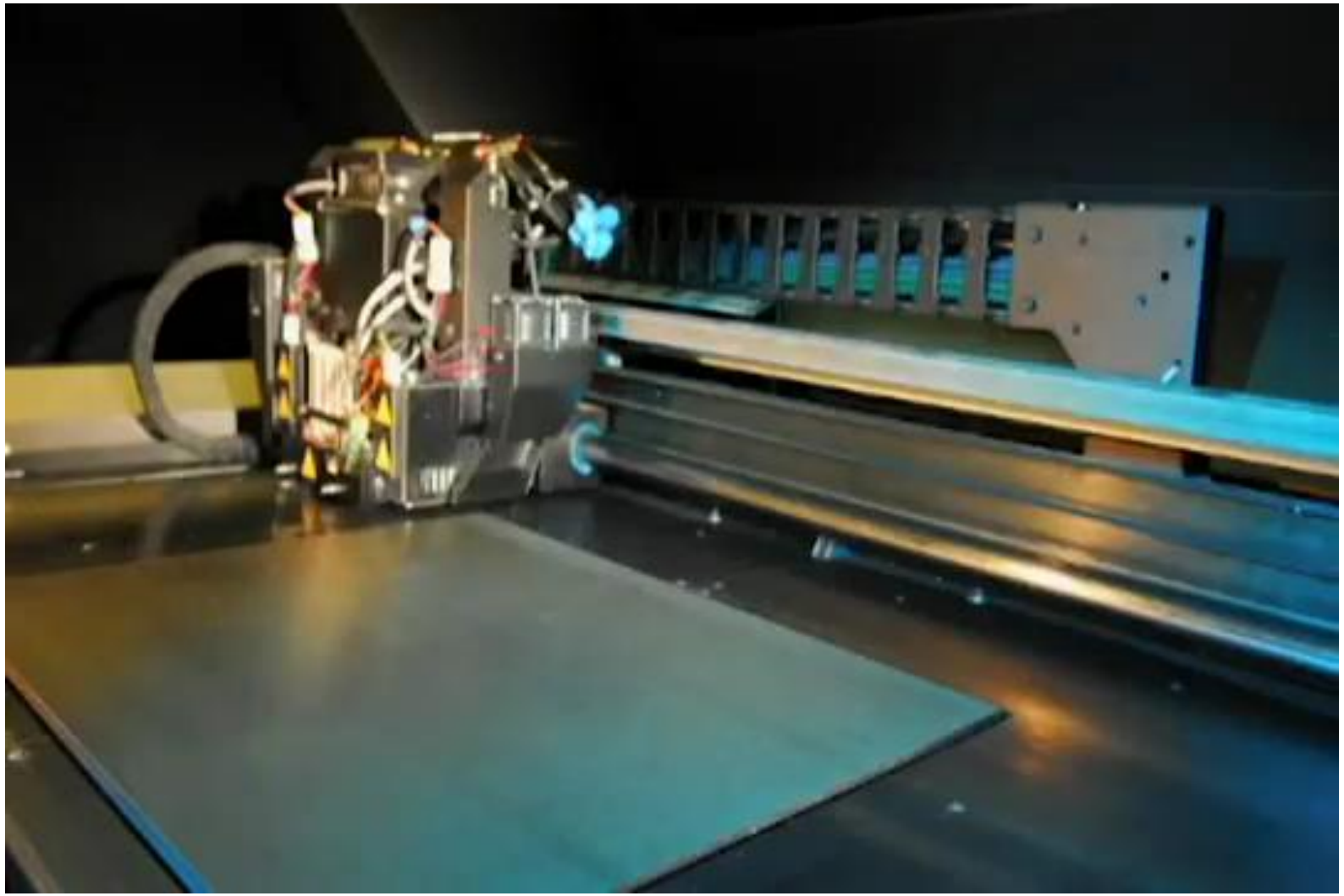
Photopolymer Phase Change Inkjets



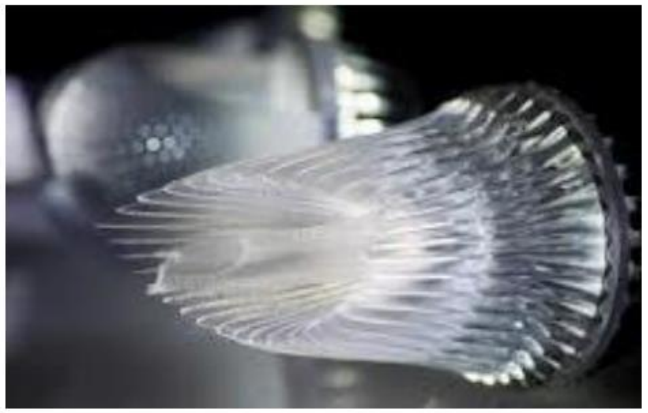
Photopolymer Phase Change Inkjets



Photopolymer Phase Change Inkjets

- Bio-compatible
- High-temperature
- ABS-like
- Transparent
- Opaque
- Rigid
- Rubber-like

Photopolymer Phase Change Inkjets



Exotic Technologies

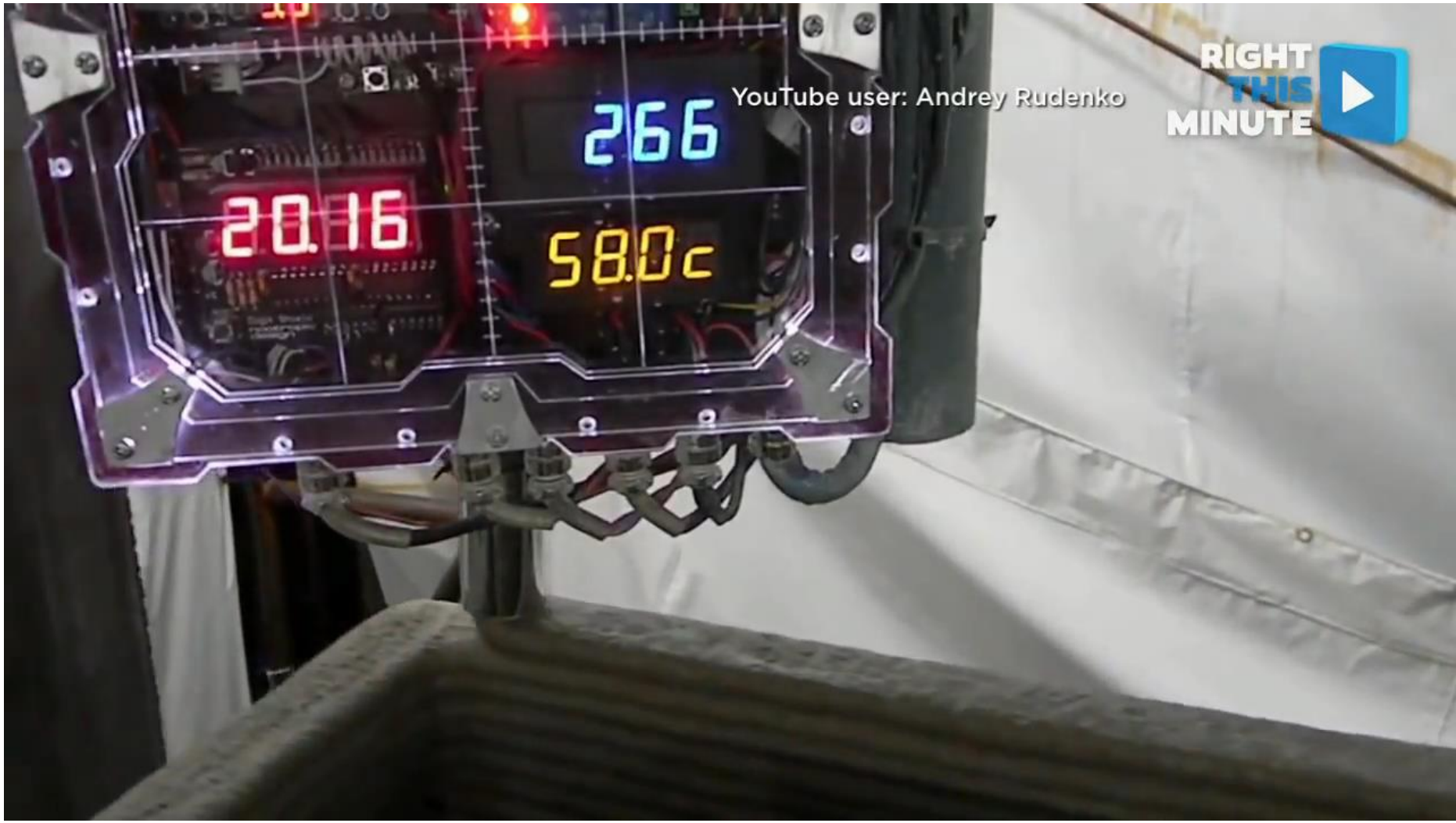
- Food

Exotic Technologies

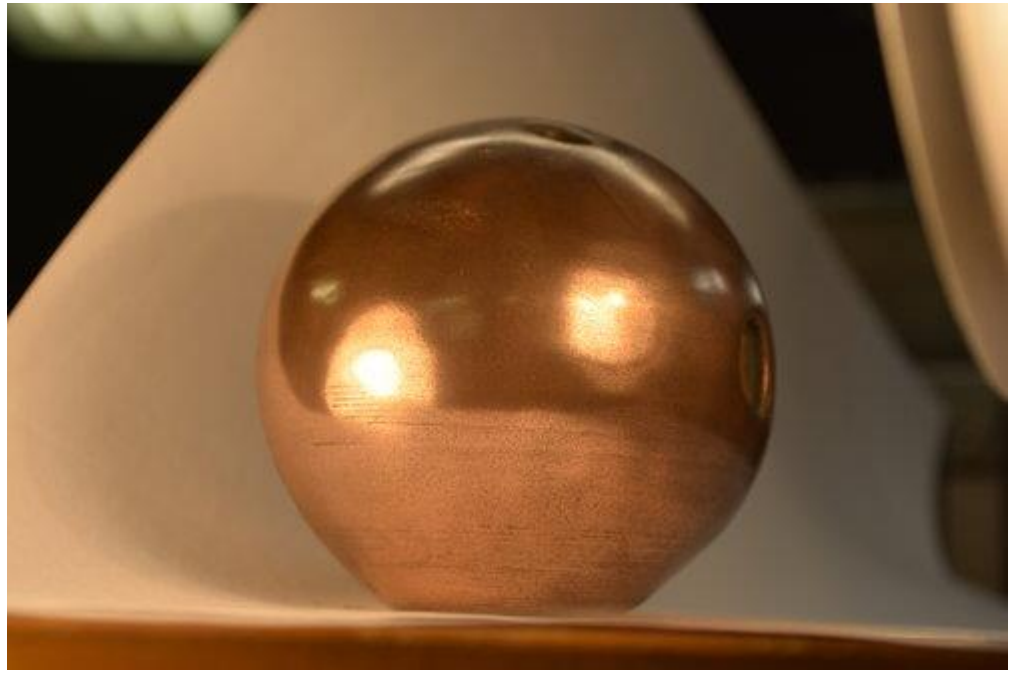
- Food
- 3D Pens

Exotic Technologies

- Food
- 3D Pens
- Construction



Copper PLA Filament



Conductive Filament

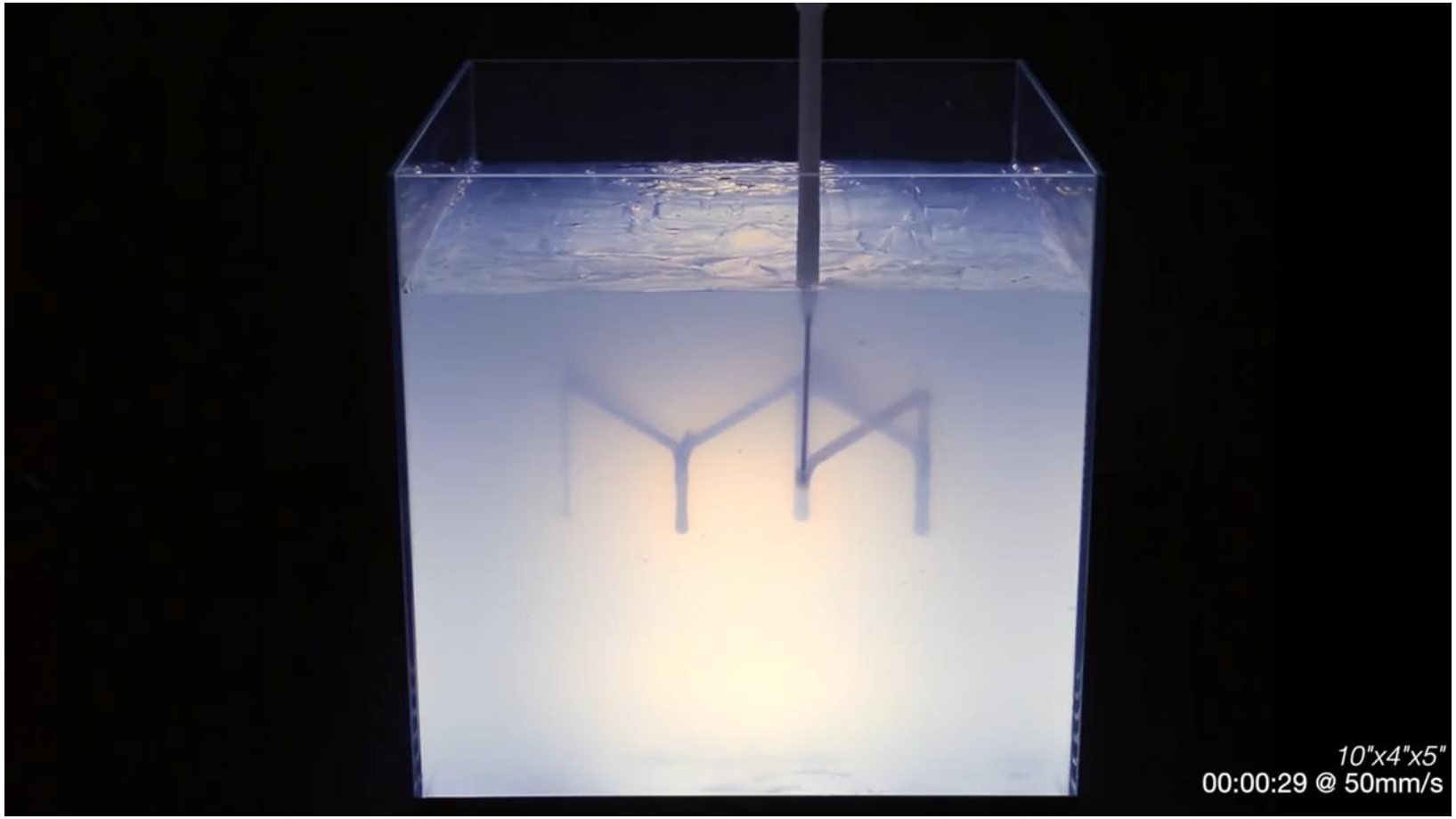
Markforged – Mark One

https://www.youtube.com/watch?v=Y5wjjDBdgeE

Ceramics Printing

Robotic Clay Printing

Rapid Liquid Printing



https://www.youtube.com/watch?v=8p7CSNbX8vM

Applications

- Jewelry
- Dental and Medical Industries
- Footwear
- Architecture, Engineering and Construction
- Aerospace
- Automotive
- Consumer Home Products
- Toys and Gadgets
- Art
- Education

Applications

Jewelry (direct metal printing and casting patterns)






Applications

Dental and Medical Industries

Crowns, copings, bridges

Custom Hearing Aids

Implants

Prosthetics

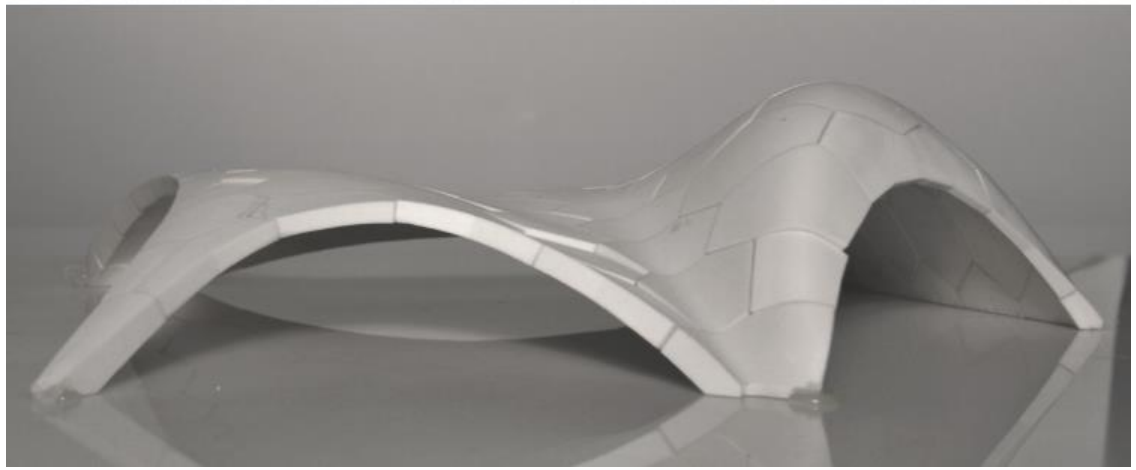
Applications

Footwear

Applications

Architecture

Models

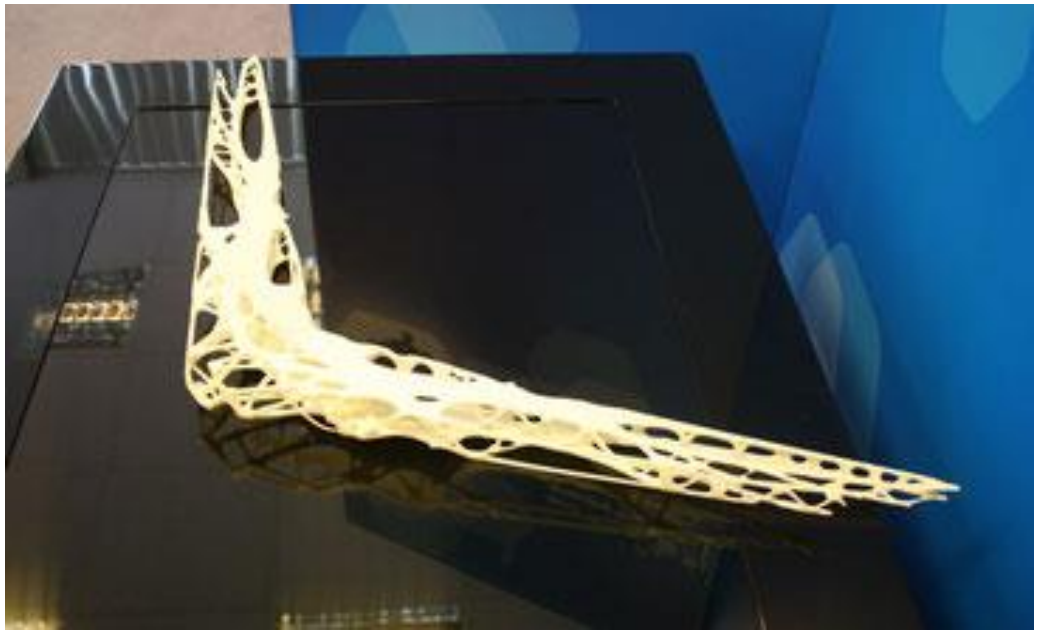


Molds

Applications

Aerospace

Airbus wing brackets



3D printed wing structure resembling the skeleton of birds

Applications

Automotive

Honeycomb Tires

3D Printed Ventilation Prototype
(High Temperature 3D Printing Material)

Applications

Consumer Home Products

Lamp

Egg cup

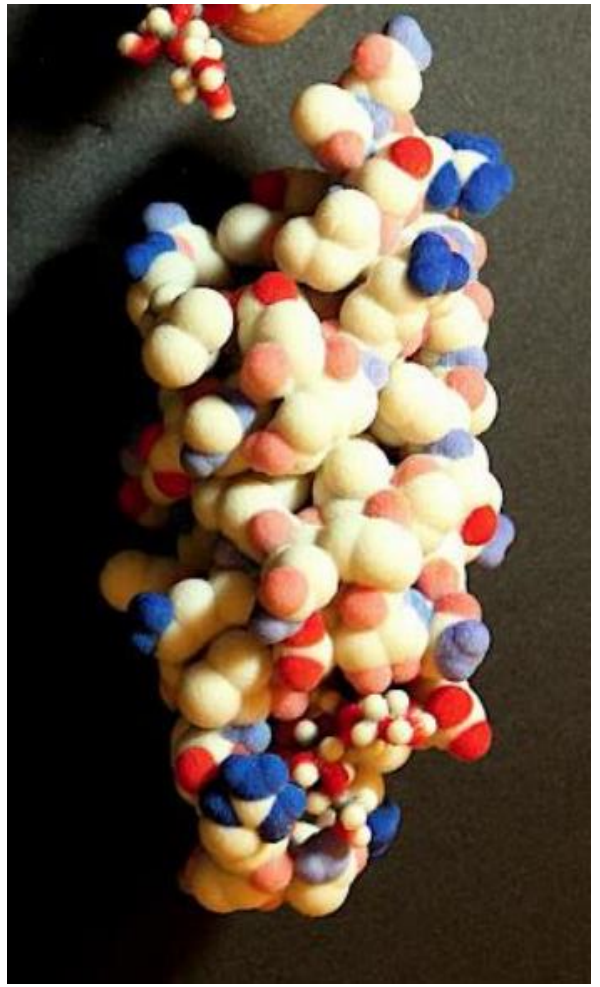
Espresso Cup

Platter

Pencil bowl

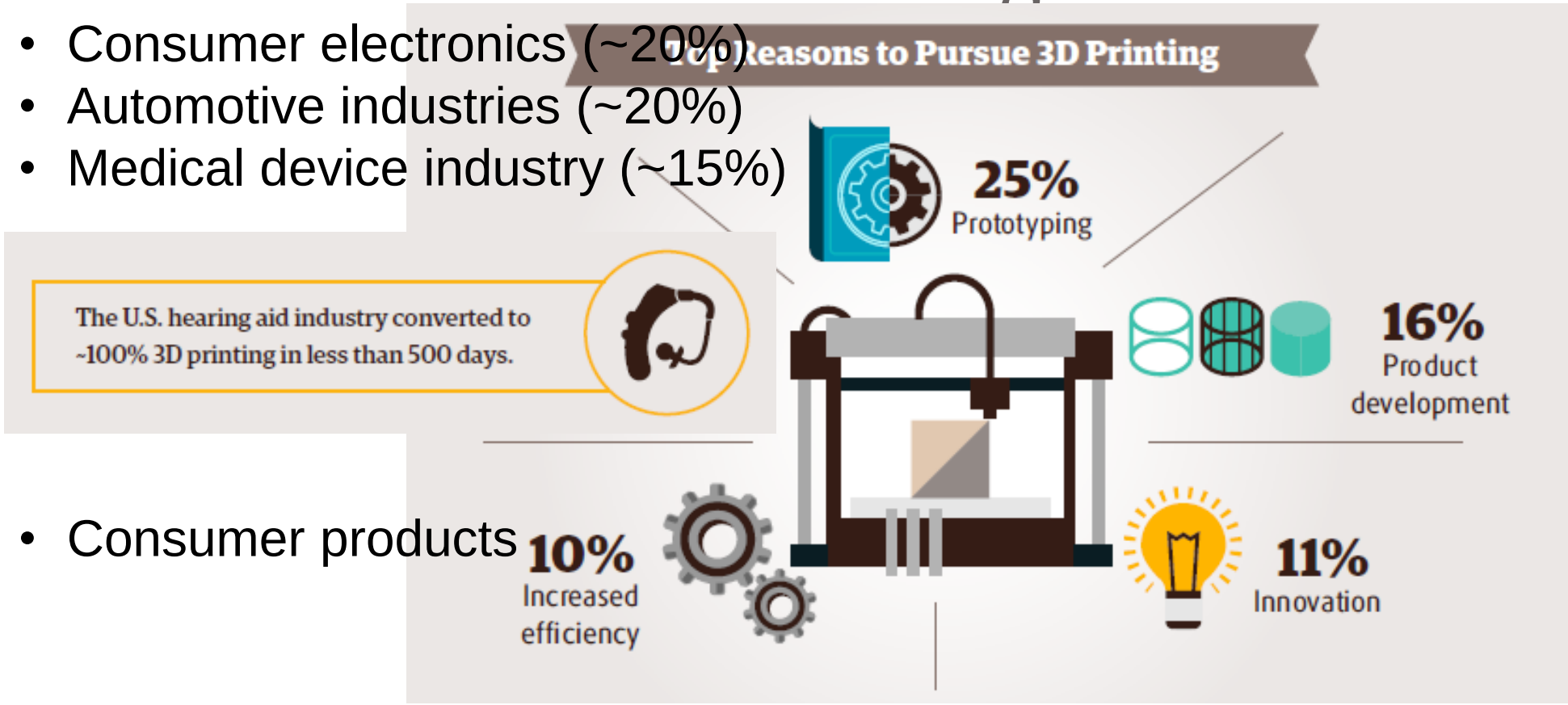
Applications

Toys, Art & Education



Additive Manufacturing

- Consumer electronics (~20%)
- Automotive industries (~20%)
- Medical device industry (~15%)



- Consumer products

https://www.ups.com/media/en/3D_Printing_executive_summary.pdf

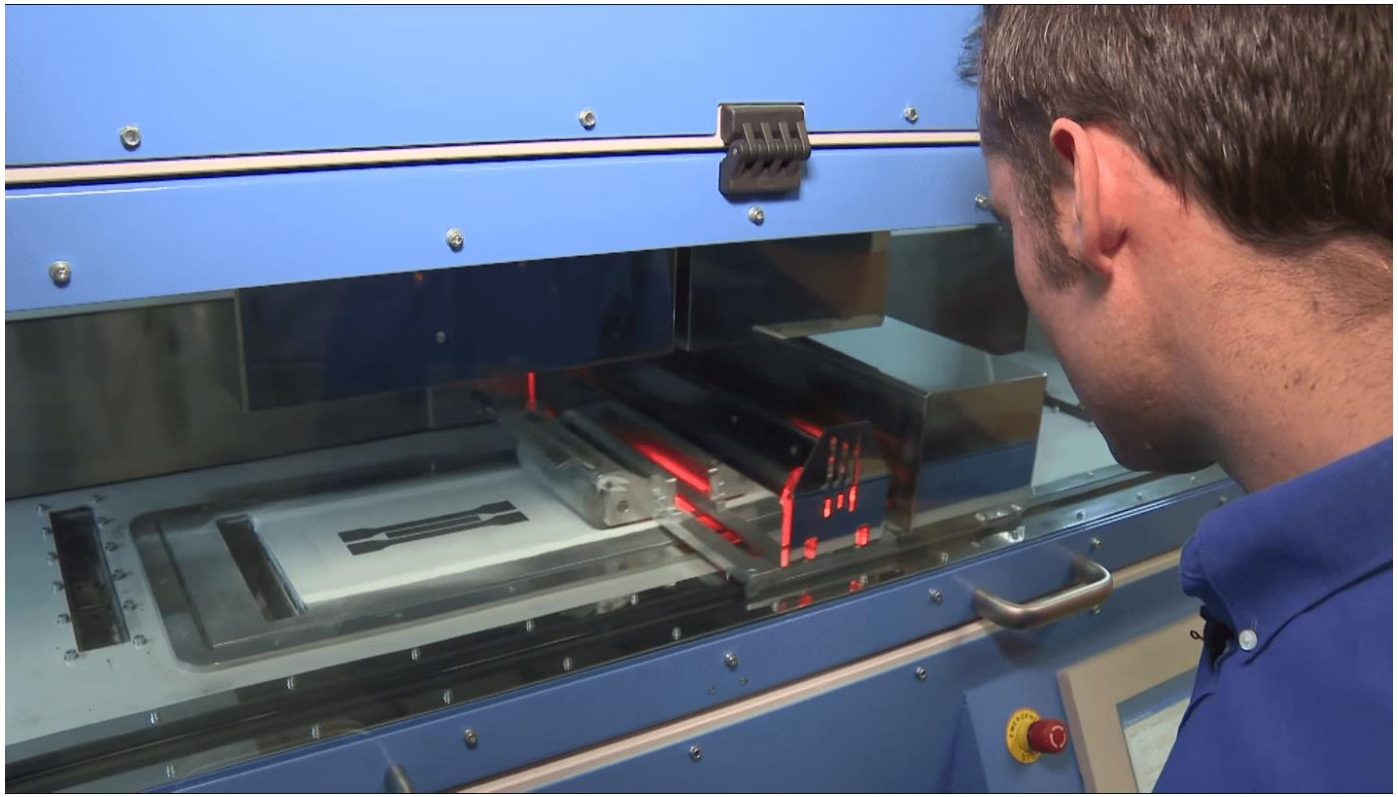
Agenda

- What is additive manufacturing?
- **Challenges**
  - **Disciplines**
- Computational fabrication and graphics?
- Computational fabrication in graphics

Challenges

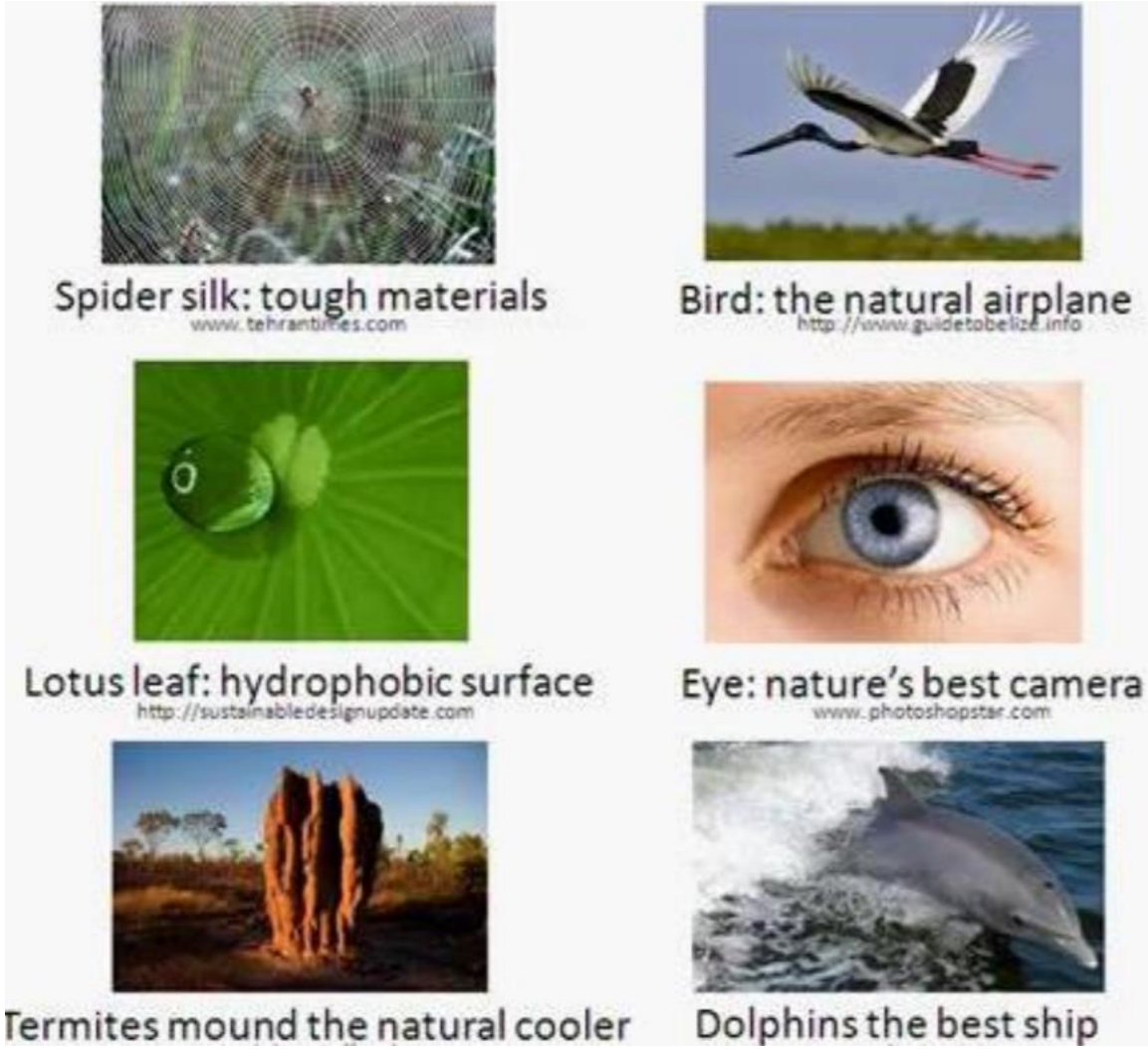
Mechanical + Electrical Engineering Challenges

- Slow – Printing 5’’ x 5’’ x 5’’ object takes 10+ hours
- Expensive – $100 / lb
- Print Volume



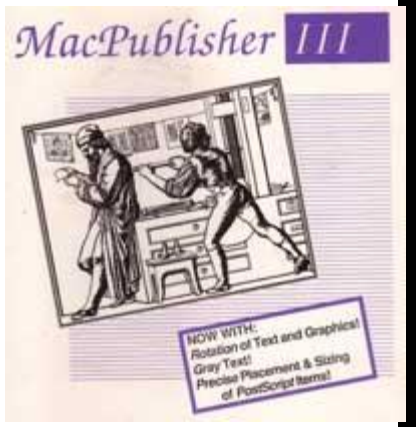
Challenges

- Material Challenges
  - Better control over physical properties:
    - Strength / weight
    - Deformability (stretchy, flexible)
    - Magnetism, conductivity
    - Heat resistance and transfer
  - Better control over optical properties:
    - Color
    - Shininess
    - Reflectivity
    - Roughness
    - Translucency
    - BRDF…
  - Interface between materials



Additive Manufacturing Challenges

Software



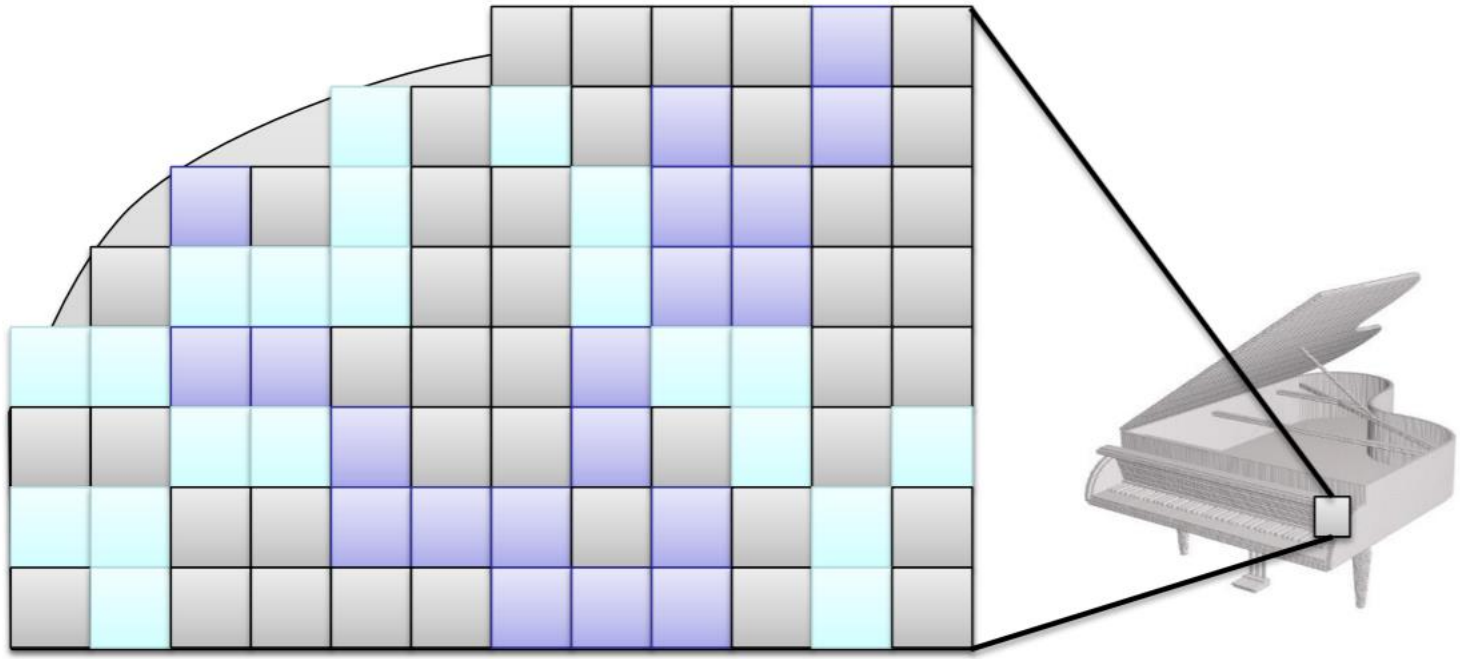
Challenges

Software Challenges

Challenges

Software Challenges

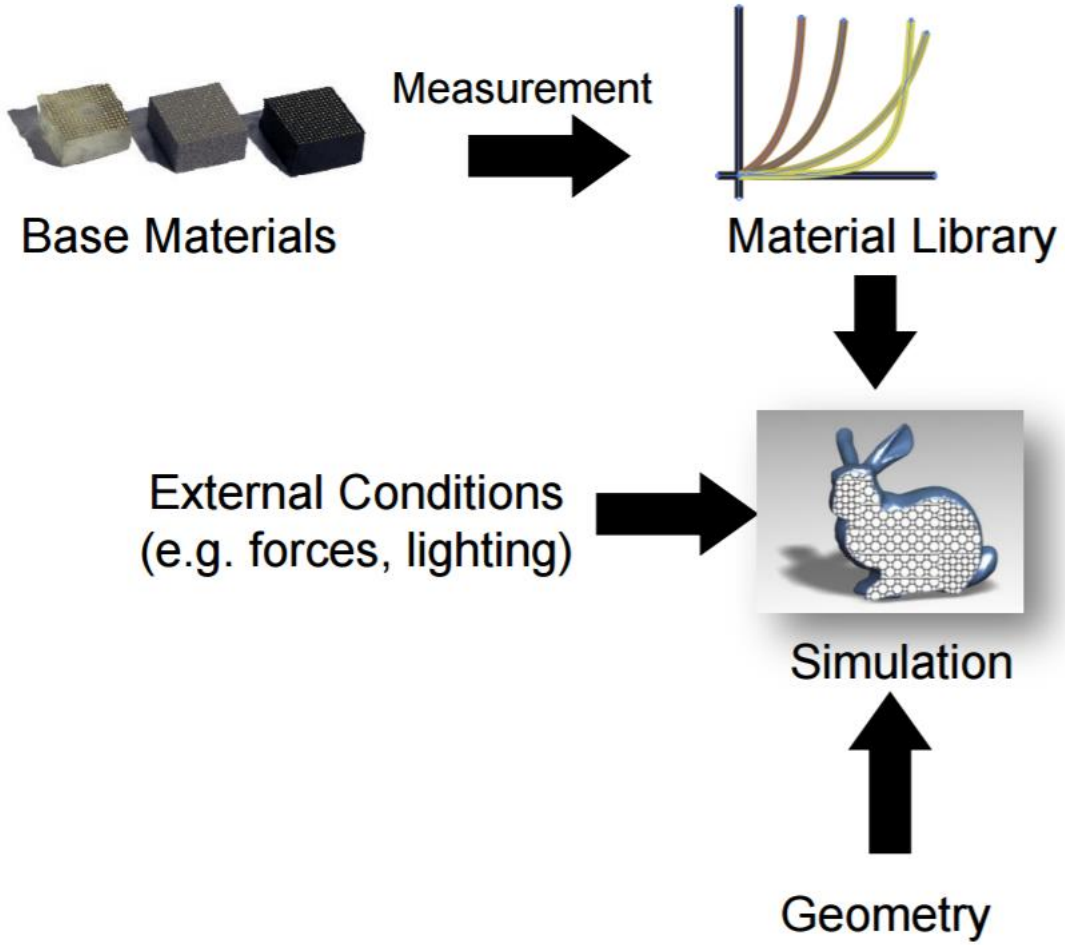
- Data Requirements & Representations
  - Giga voxels/inch^3 , Tera voxels/foot^3



Challenges

Software Challenges

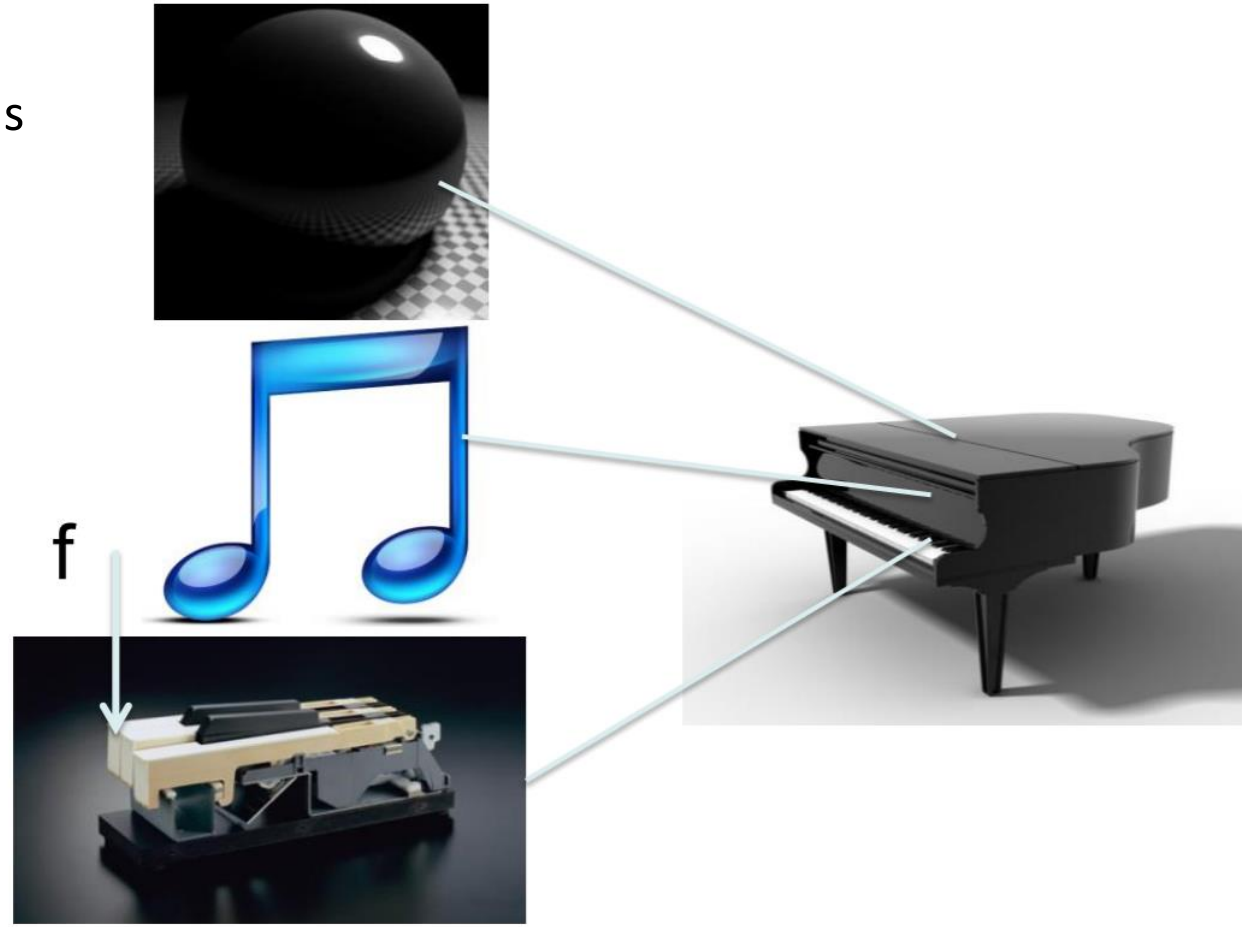
- Data Requirements & Representations
- Measurement & Simulation



Challenges

Software Challenges

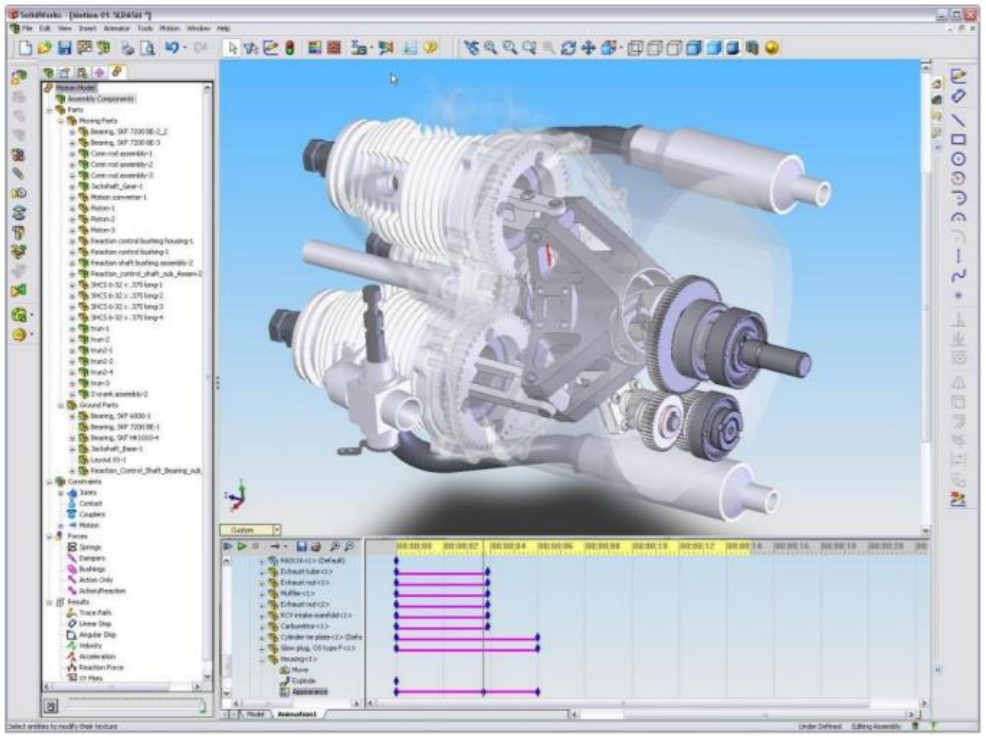
- Data Requirements & Representations
- Measurement & Simulation
- Optimization

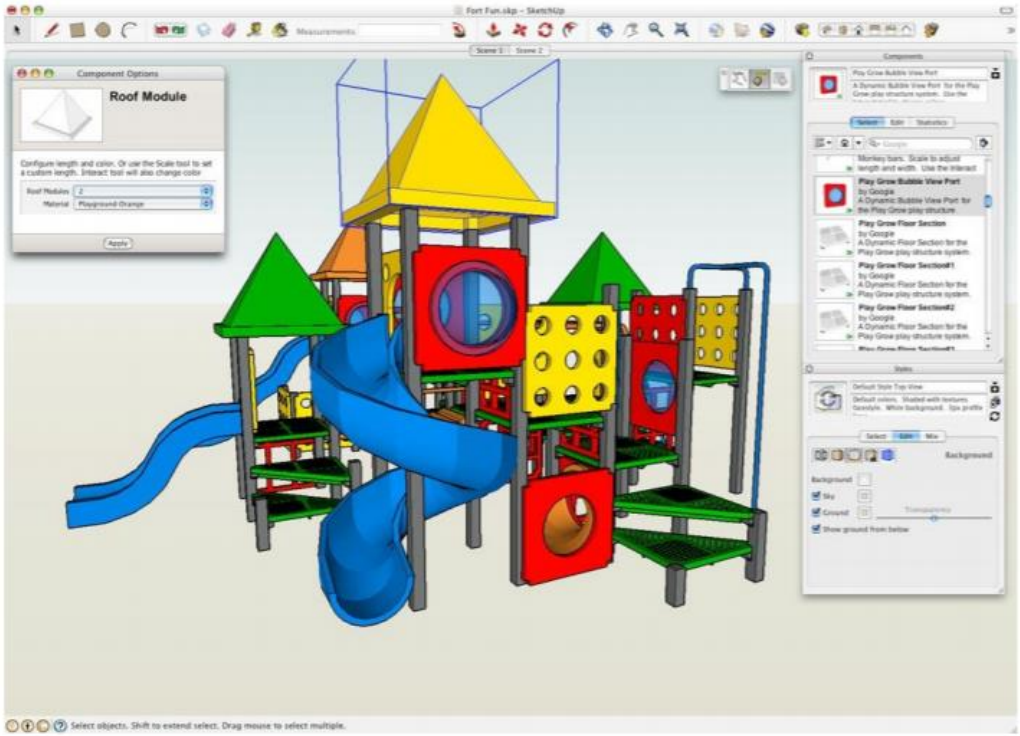


Challenges

Software Challenges

- Data Requirements & Representations
- Measurement & Simulation
- Optimization
- Design





Agenda

- What is additive manufacturing?
- Challenges
- **Computational fabrication and graphics?**
  - **Appearance**
  - **Physical simulation**
  - **Geometry Processing**
  - **Animation**
- Computational fabrication in graphics

Fabrication and Graphics

Appearance

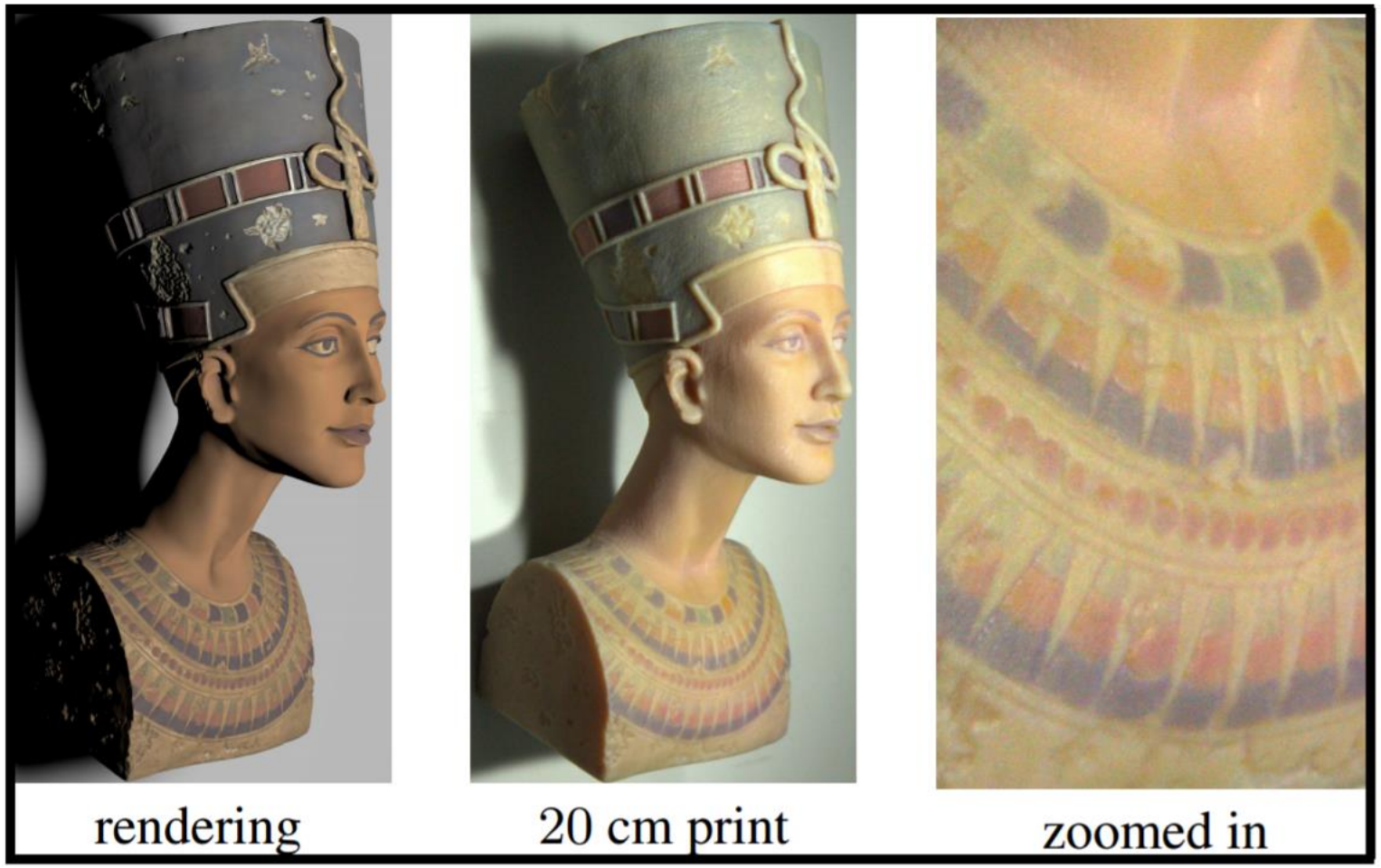
- Halftoning

Dual-Color Mixing for Fused Deposition Modeling Printers [2014]

Fabrication and Graphics

Appearance

- Halftoning



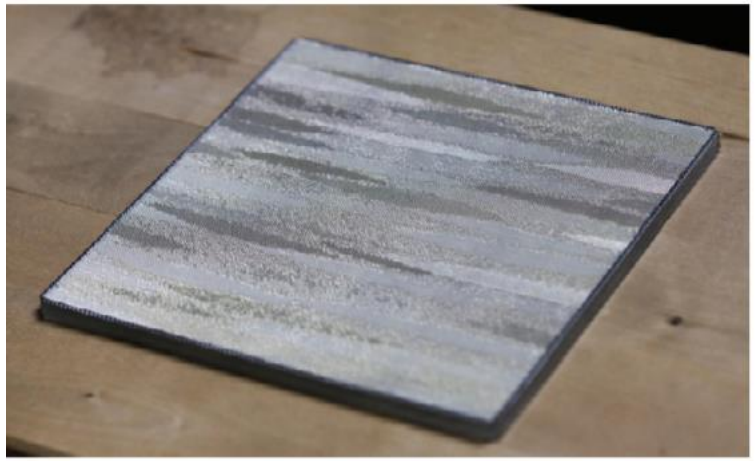
Pushing the limits of 3d color printing: Error diffusion with translucent materials [2015]

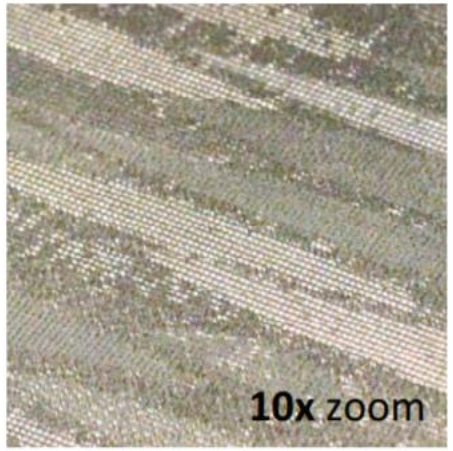
Fabrication and Graphics

Appearance

- Halftoning
- Caustics
- Reflectance
- …

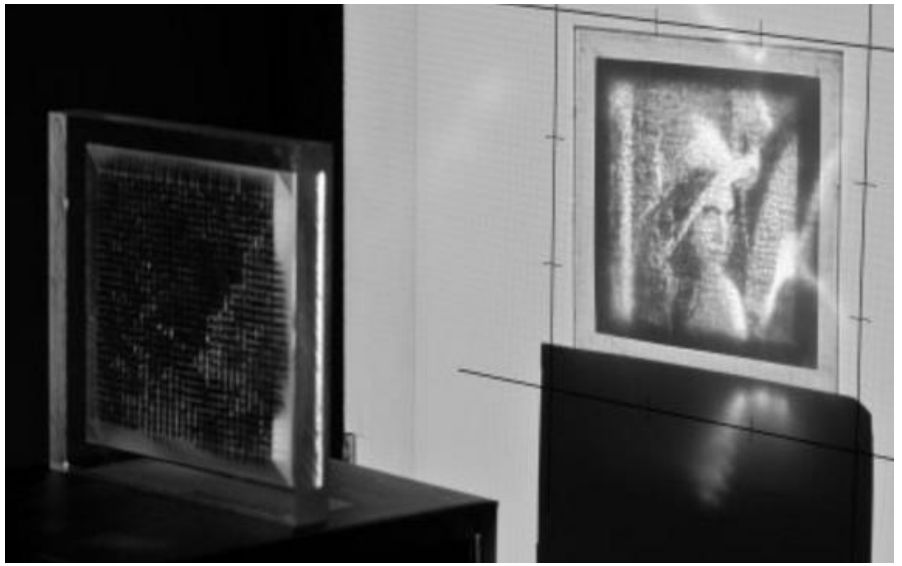
ShadowPIX: Multiple Images from Self-Shadowing [2012]





Bi-Scale Appearance Fabrication [2013]

Reliefs as images [2010]



Goal-Based Caustics [2011]

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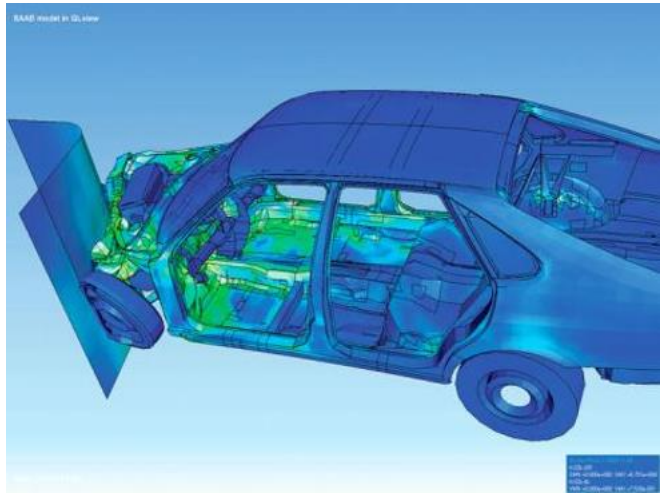
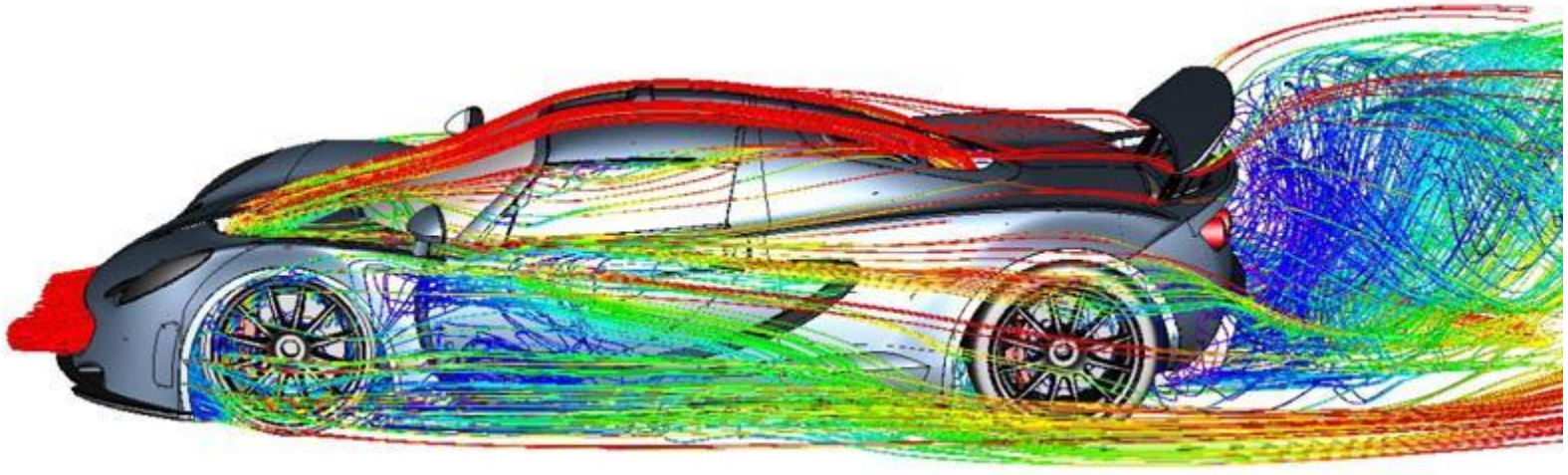
  - **Physical simulation**
  - **Geometry Processing**
  - **Animation**
- Computational fabrication in graphics

Fabrication and Graphics

Physically-based simulation

- Computational Sciences
  - **Reproduction** of physical phenomena
  - Predictive capability (accuracy!)
  - Substitute for expensive experiments

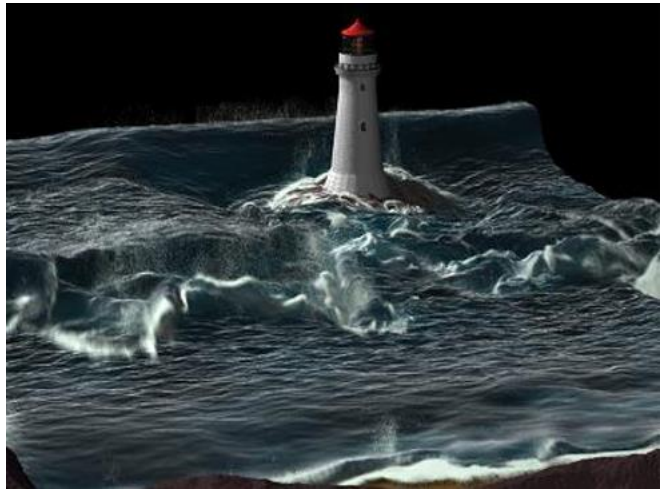




Fabrication and Graphics

Physically-based simulation

- Computational Sciences
  - **Reproduction** of physical phenomena
  - Predictive capability (accuracy!)
  - Substitute for expensive experiments
- Computer Graphics
  - **Imitation** of physical phenomena
  - Visually plausible behavior
  - Speed, stability, art-directability



Fabrication and Graphics

Physically-based simulation

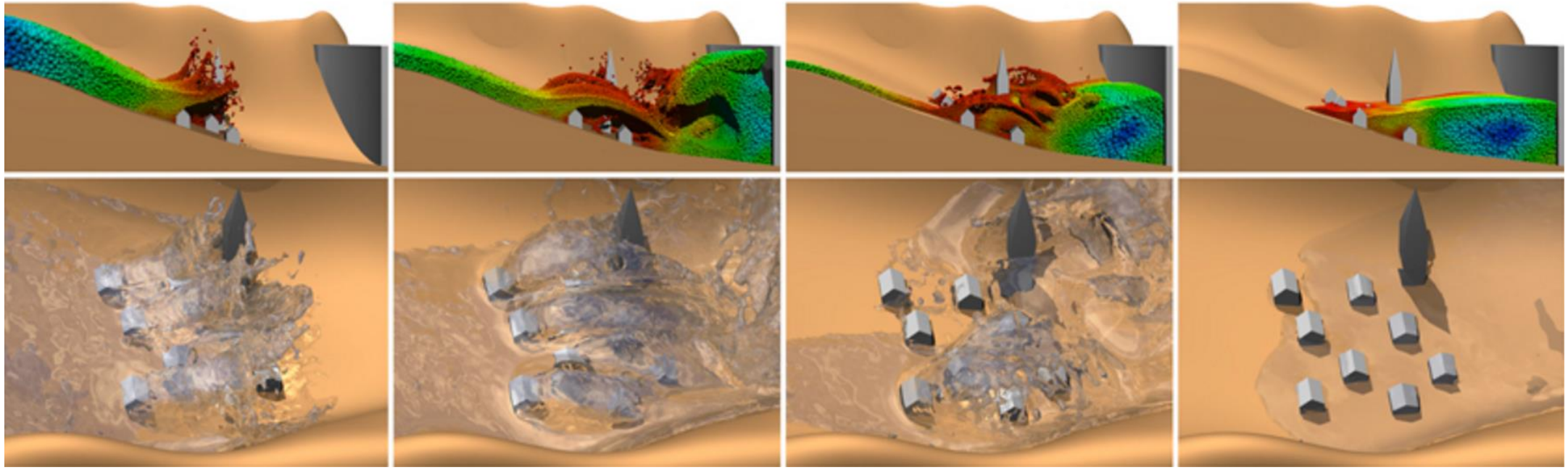
Fabrication and Graphics

Physically-based simulation

Fabrication and Graphics

Physically-based simulation

- Fluid Simulation

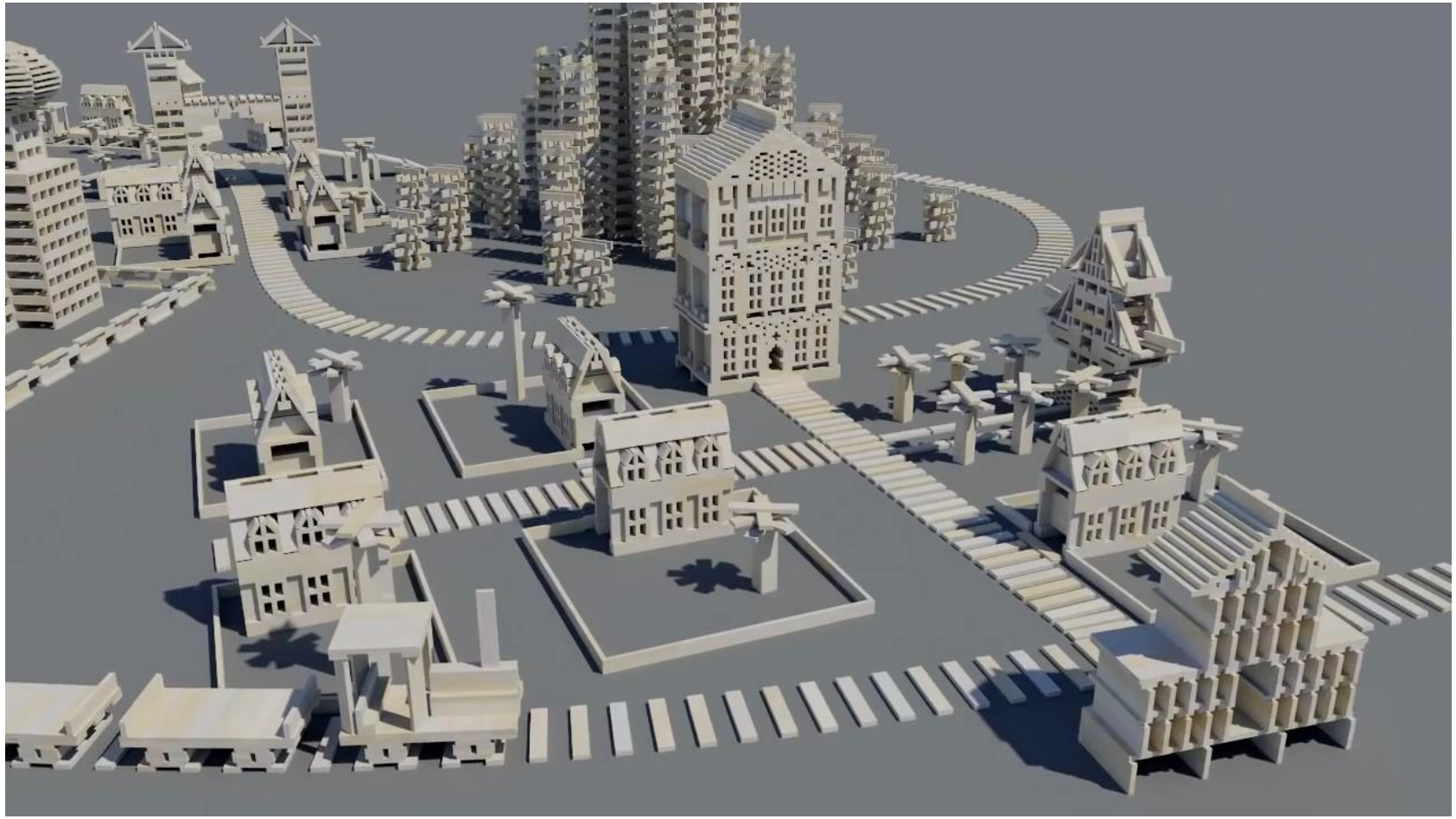


http://lgg.epfl.ch/research_physicsbased_animation.php

Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body



Fabrication and Graphics

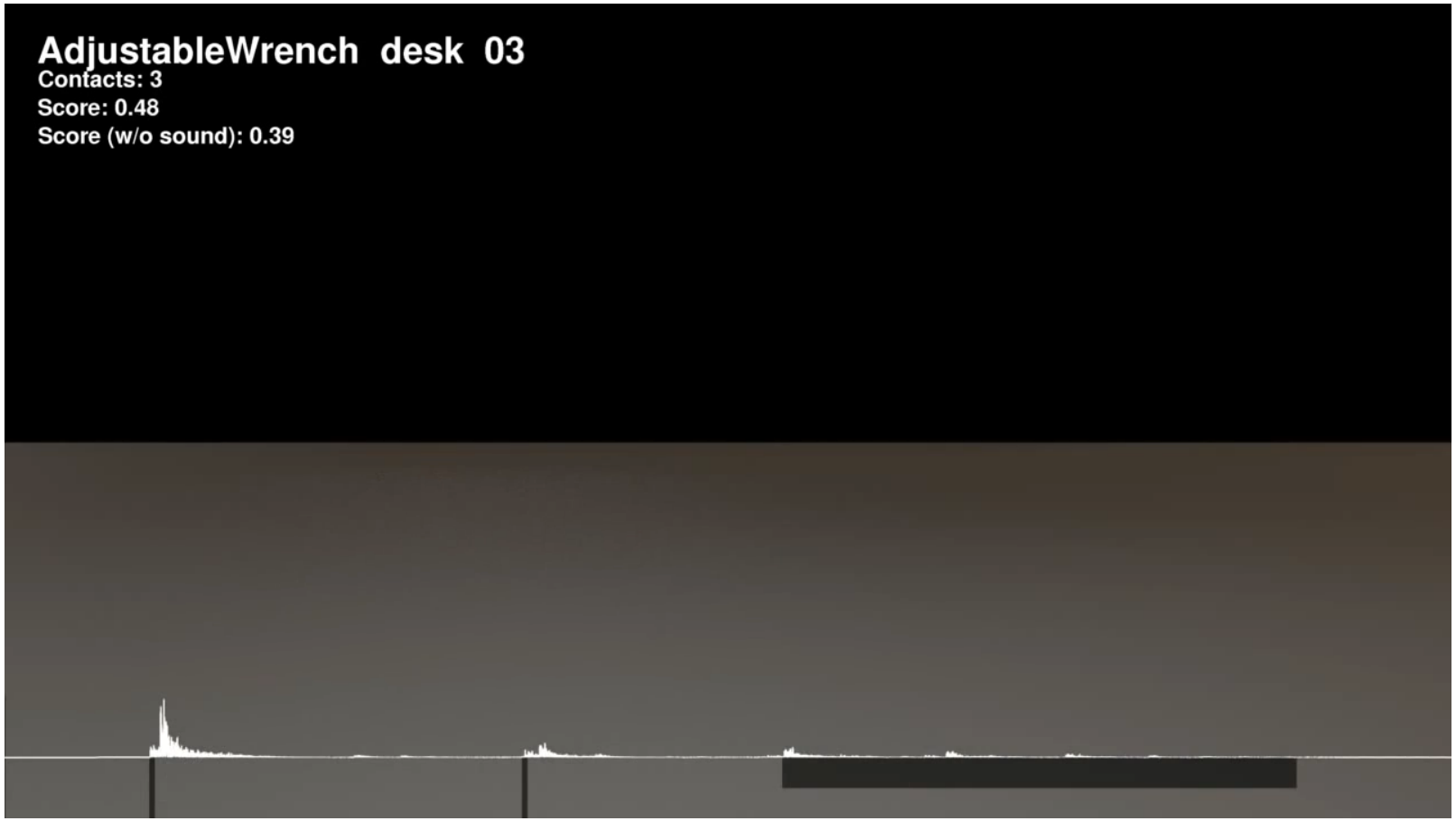
Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture

Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound

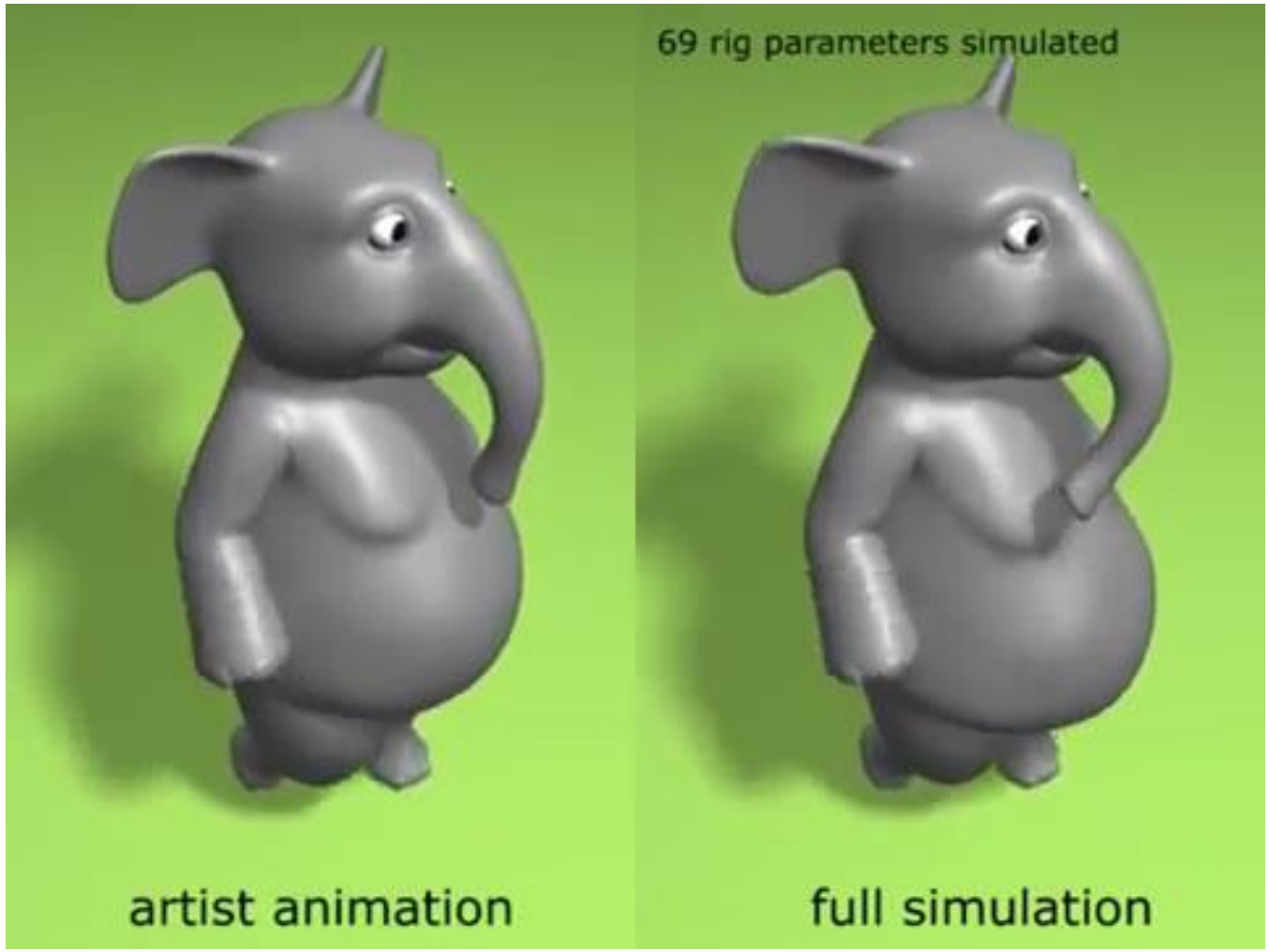


Inverse-Foley Animation: Synchronizing rigid-body motions to sound [2014]

Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**

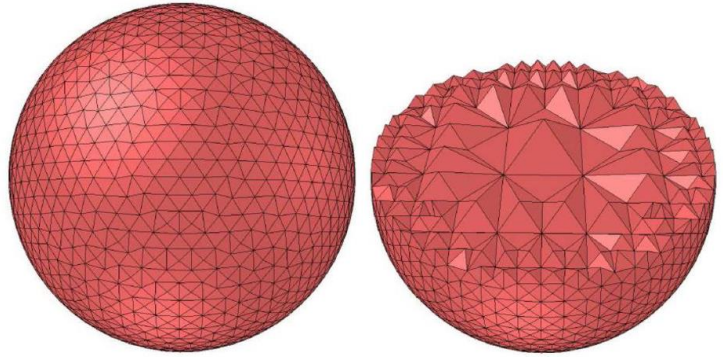


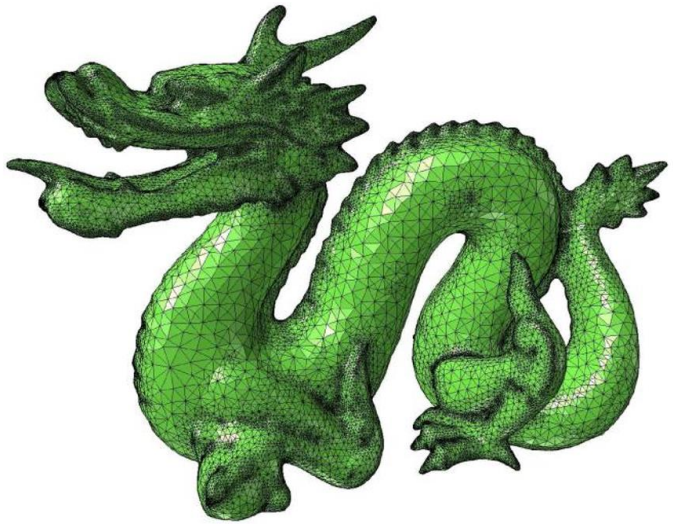
Rig-Space Physics [2012]

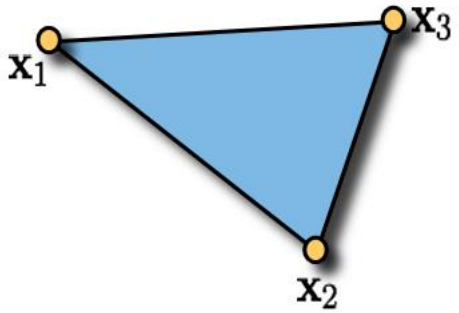
Fabrication and Graphics

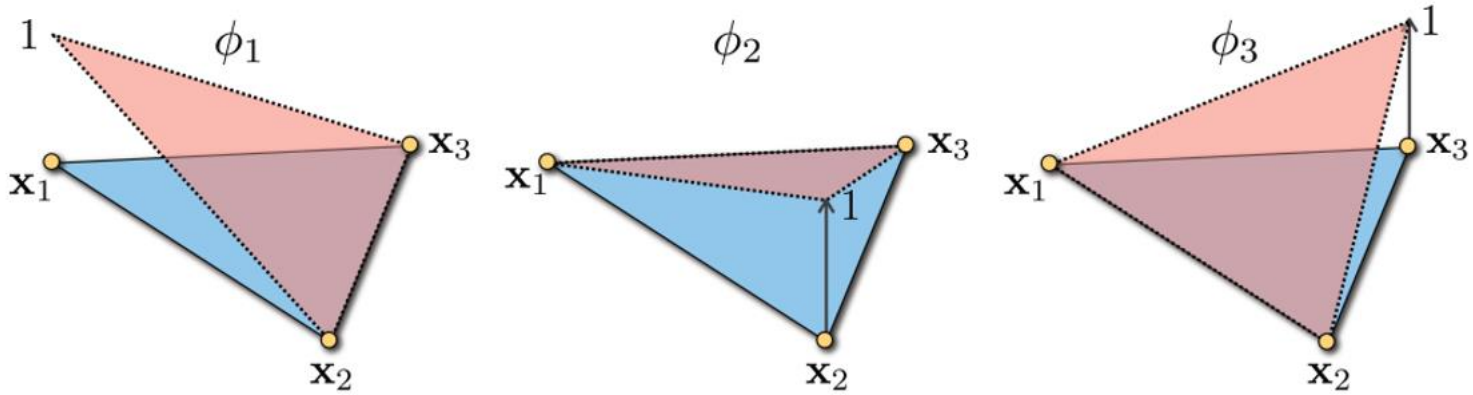
Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**
  - **FEM**





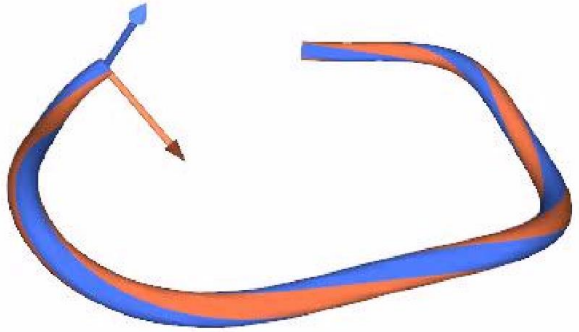


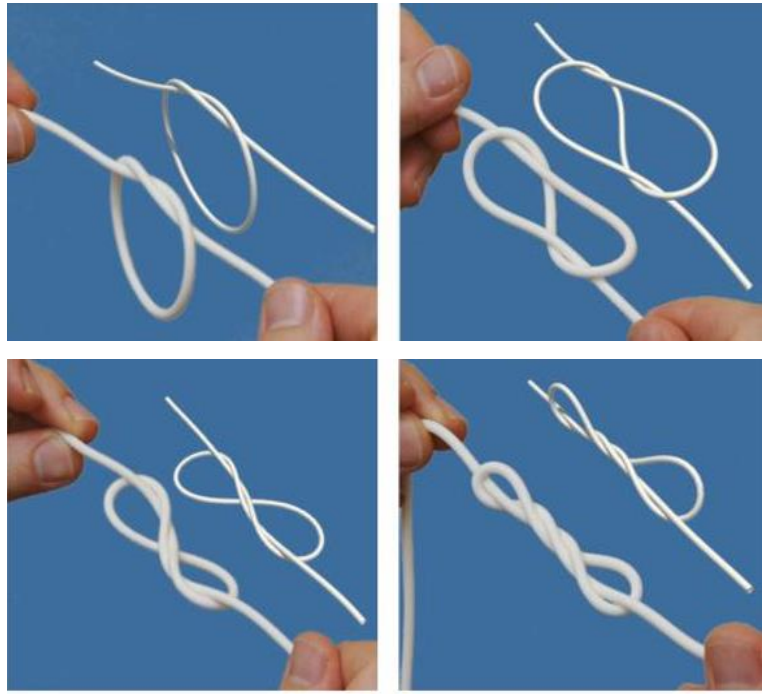


Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**
  - **FEM**
  - **Rods, shells**





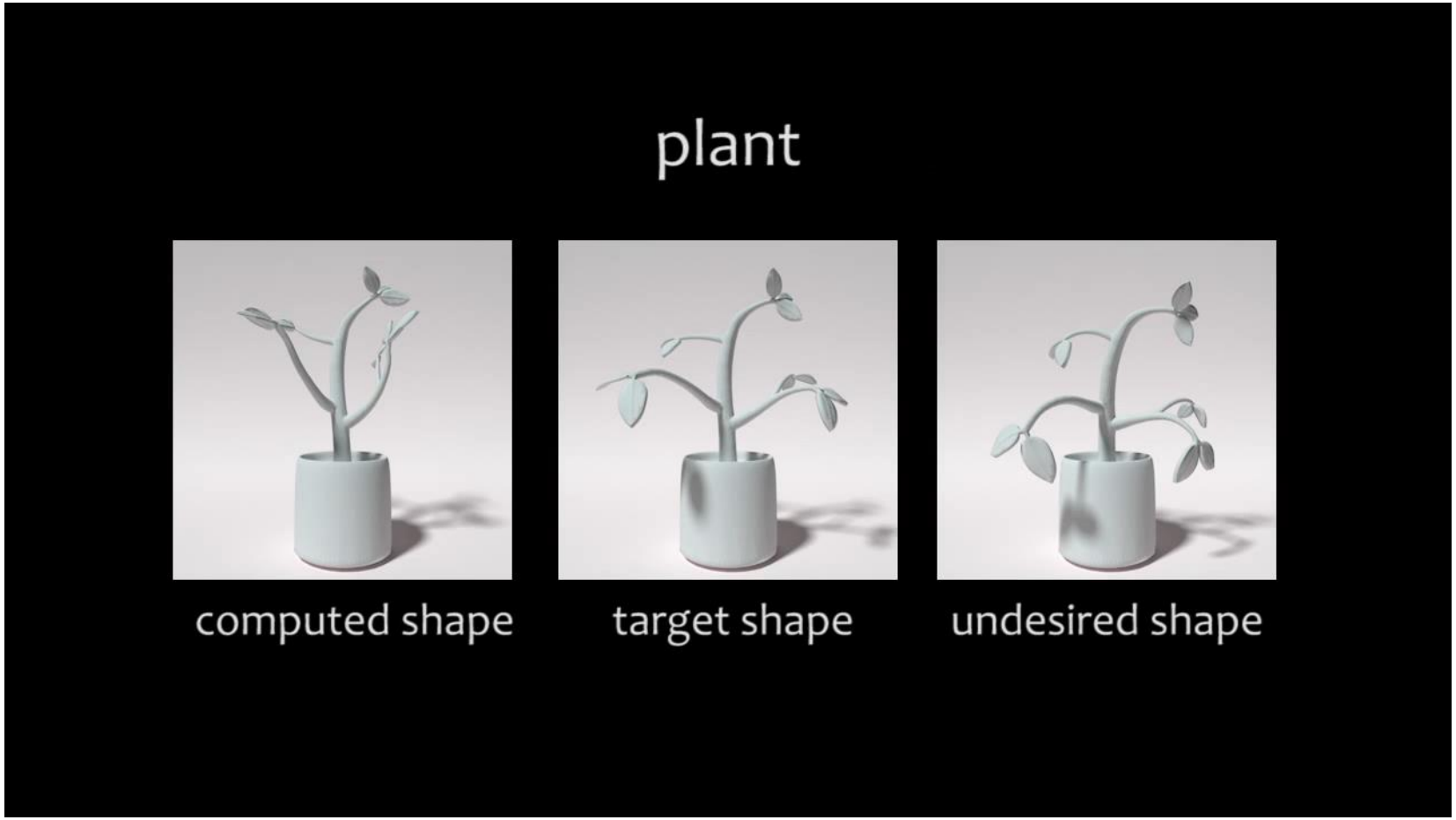
Discrete Elastic Rod model [2008]

A Consistent Bending Model for Cloth Simulation with Corotational Subdivision Finite Elements [2006]

Fabrication and Graphics

Physically-based simulation

- Fluid Simulation
- Rigid Body
- Fracture
- Sound
- **Elasticity**



An asymptotic numerical method for inverse elastic shape design [2014]

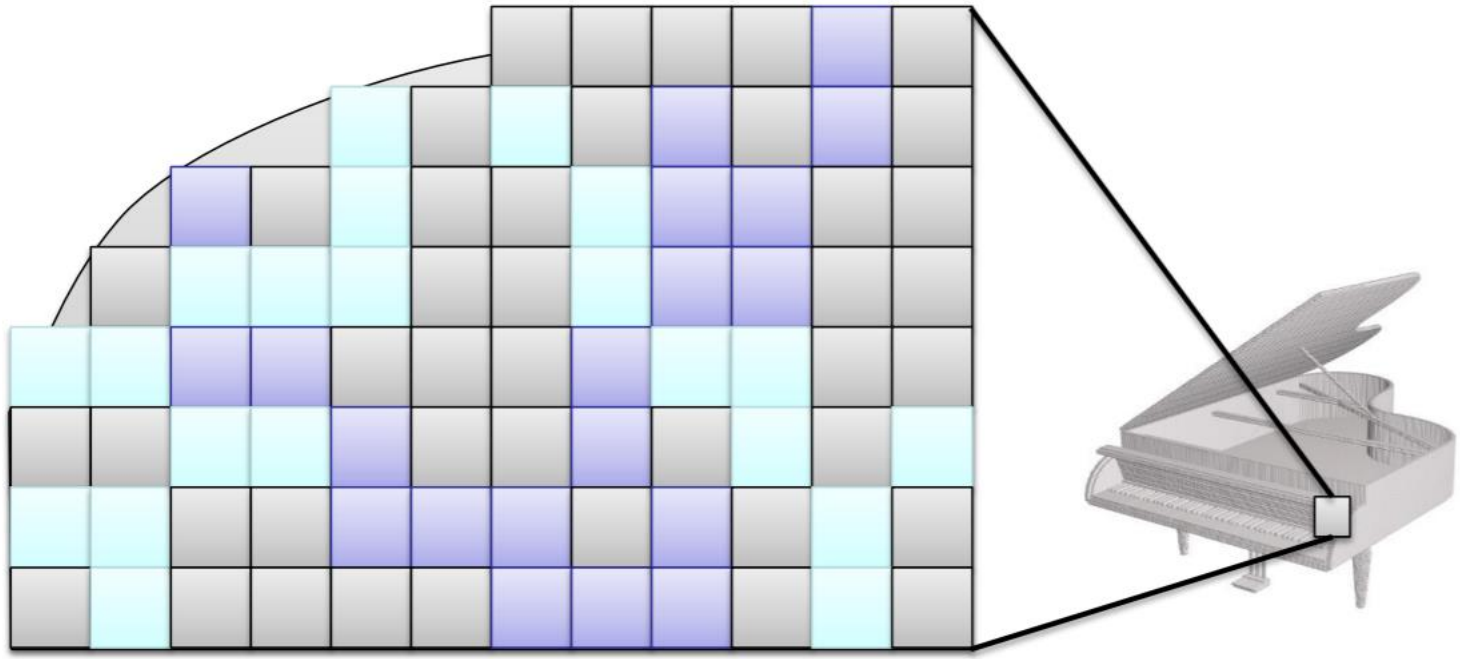
Agenda

- What is additive manufacturing?
- Challenges
- **Computational fabrication and graphics?**
  - **Appearance**
  - **Physical simulation**
  - **Geometry Processing**
  - **Animation**
- Computational fabrication in graphics

Fabrication and Graphics

Geometry Processing

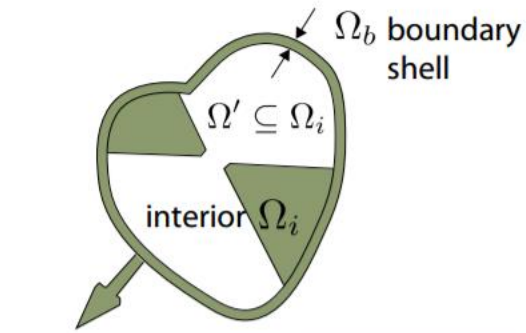
- Representations
  - Giga voxels/inch^3 , Tera voxels/foot^3

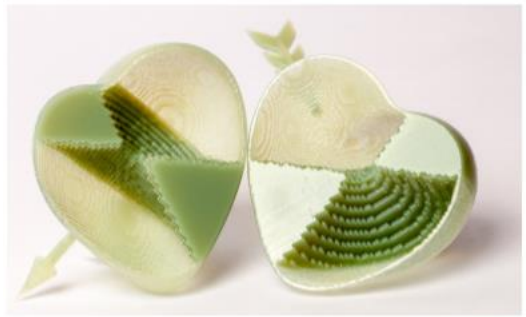


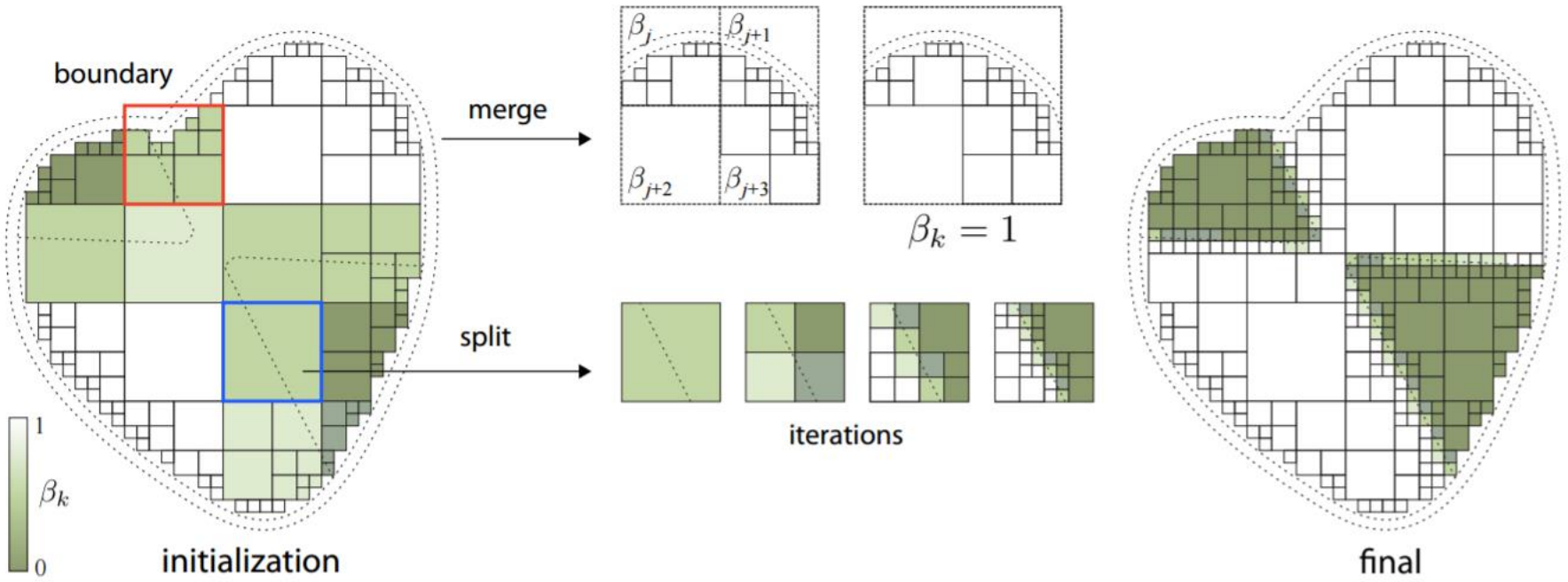
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree





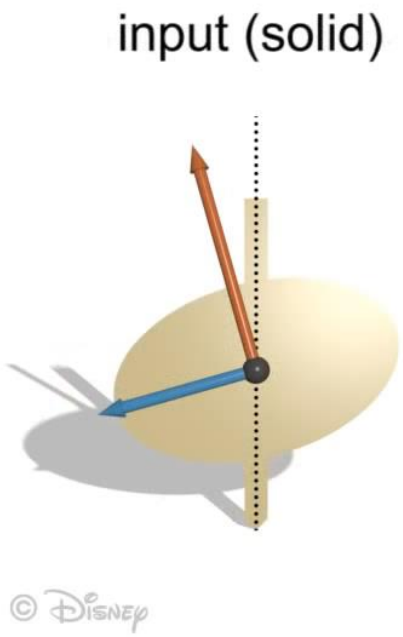


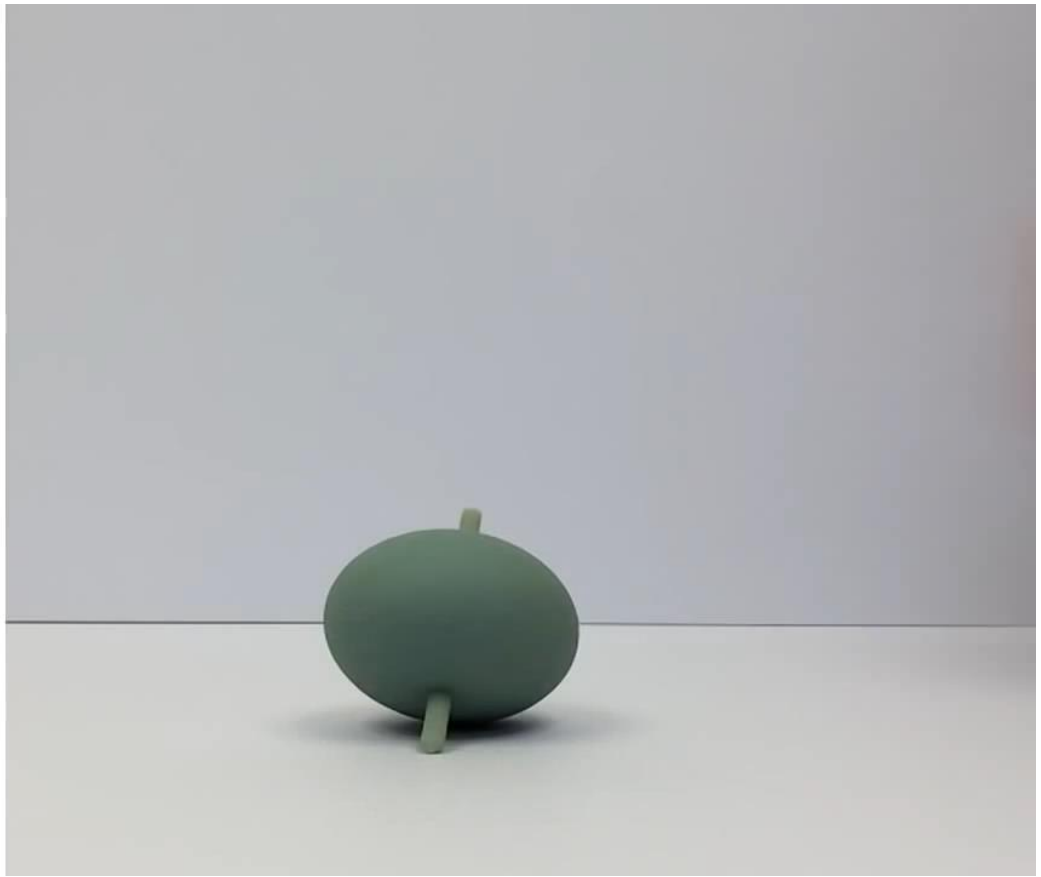
Spin-it: Optimizing moment of inertia for spinnable objects [2014]

Fabrication and Graphics

Geometry Processing

- Representations
  - Octree



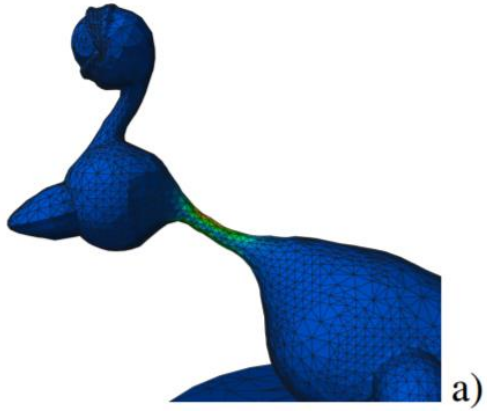


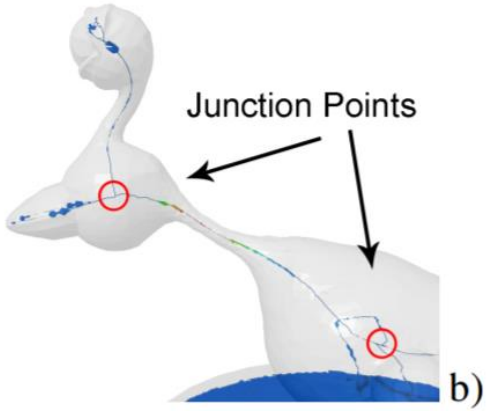
Spin-it: Optimizing moment of inertia for spinnable objects [2014]

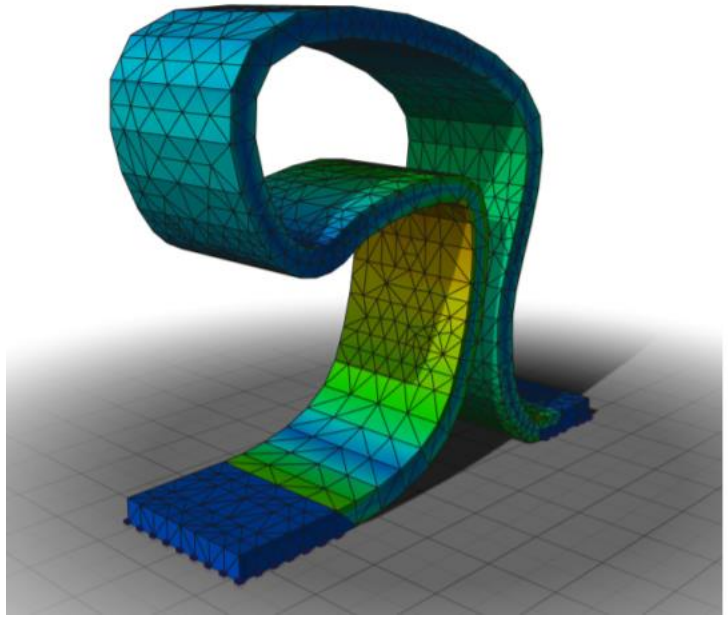
Fabrication and Graphics

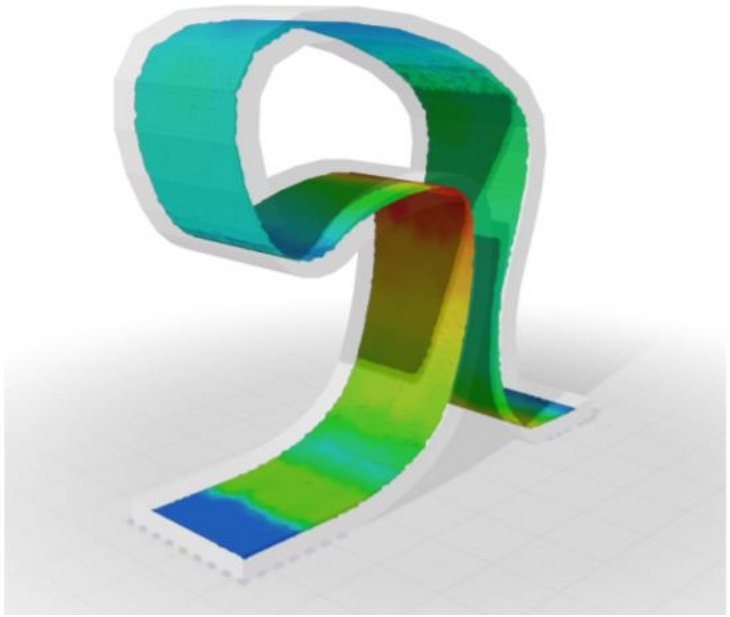
Geometry Processing

- Representations
  - Octree
  - Medial axis







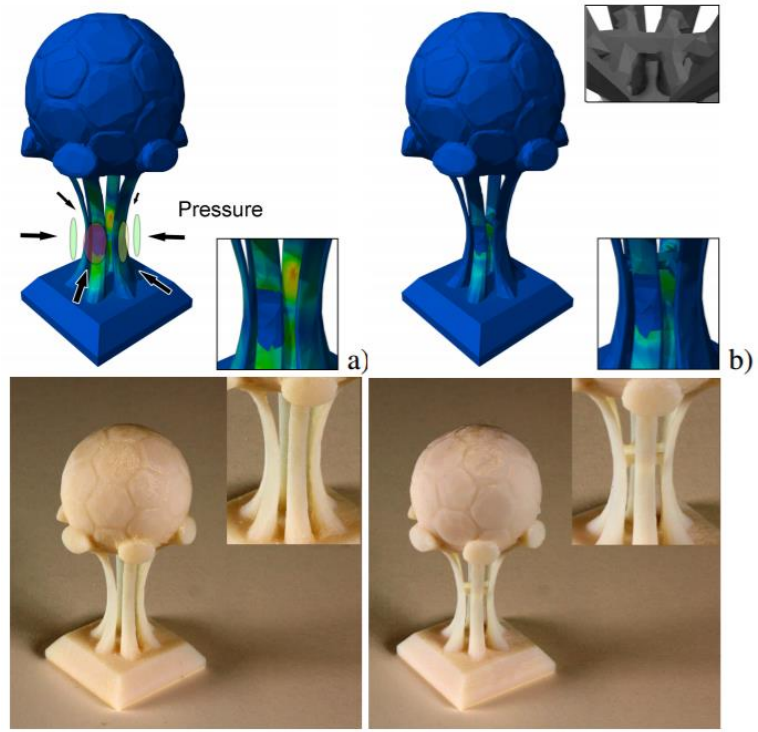


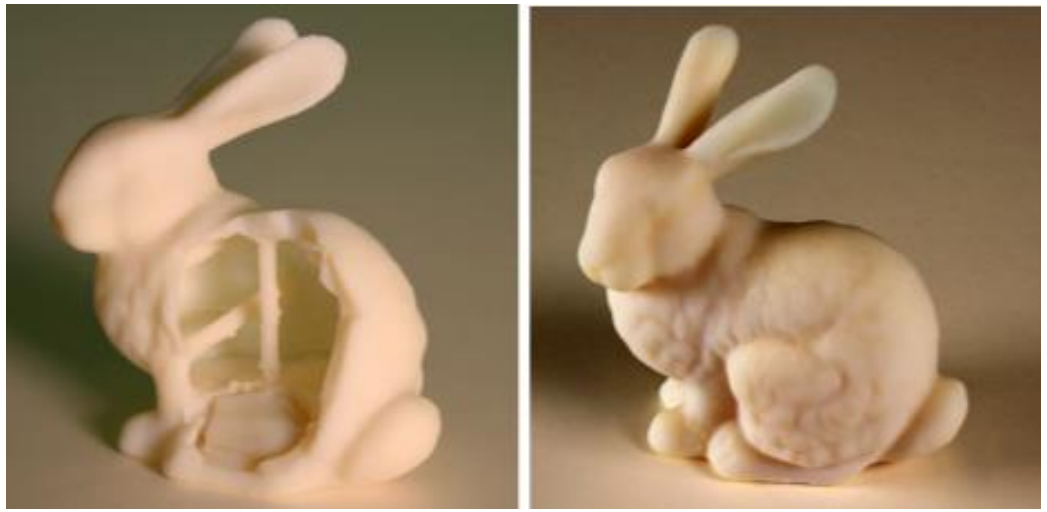
Stress relief: Improving structural strength of 3d printable objects [2012]

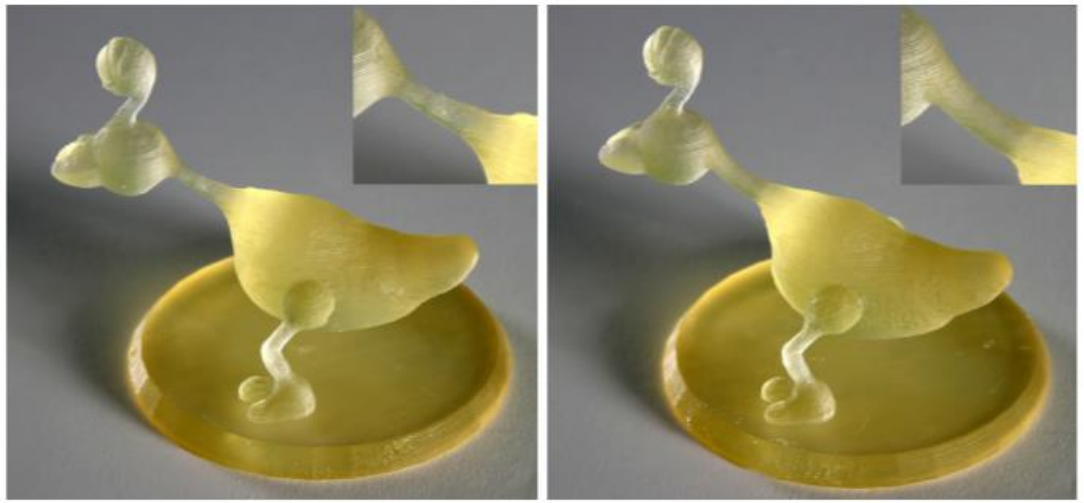
Fabrication and Graphics

Geometry Processing

- Representations
  - Octree
  - Medial axis





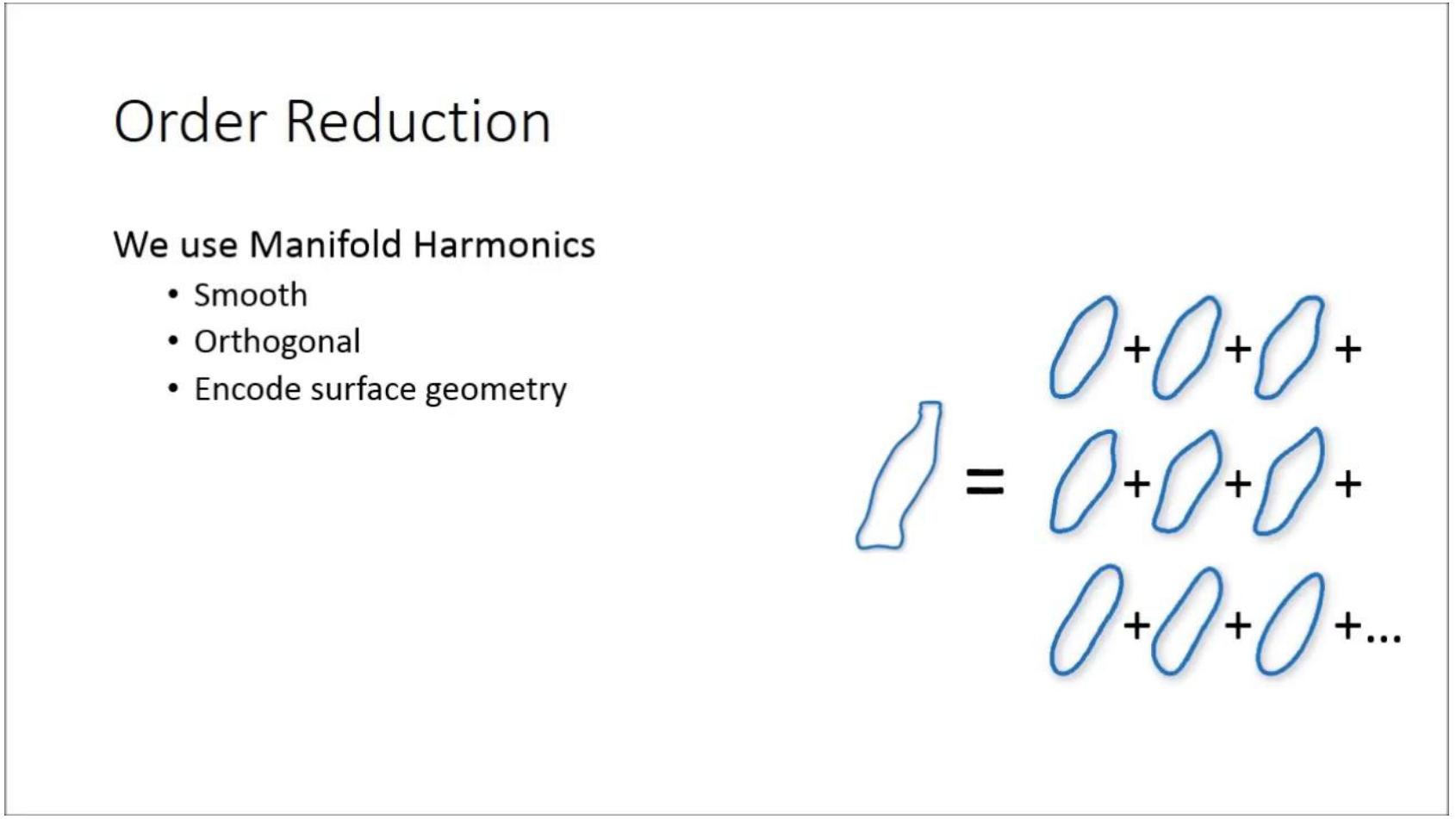


Stress relief: Improving structural strength of 3d printable objects [2012]

Fabrication and Graphics

Geometry Processing

- Representations
  - Octree
  - Medial axis
  - Spectral decomposition

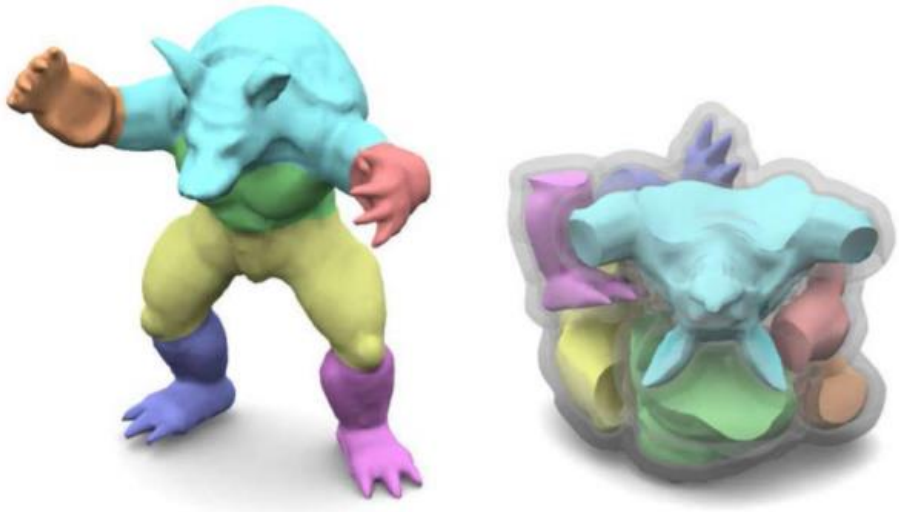


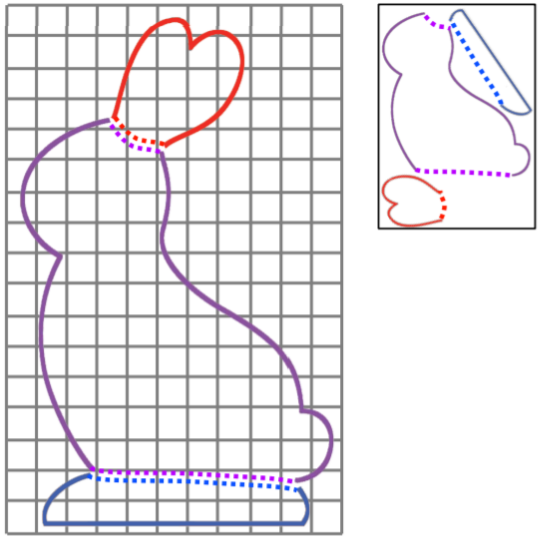
Reduced-order shape optimization using offset surfaces [2015]

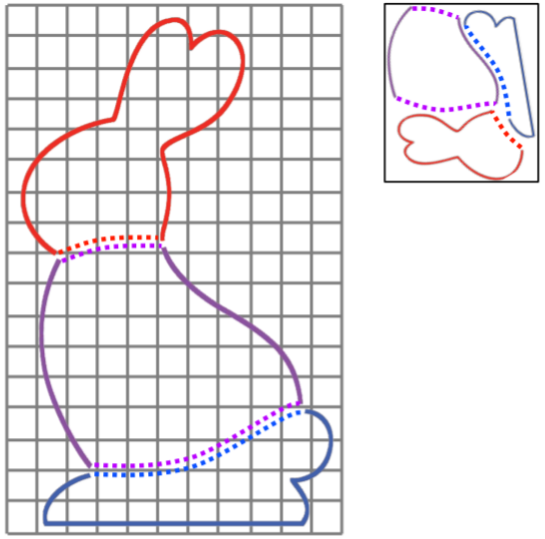
Fabrication and Graphics

Geometry Processing

- Representations
- Curvature





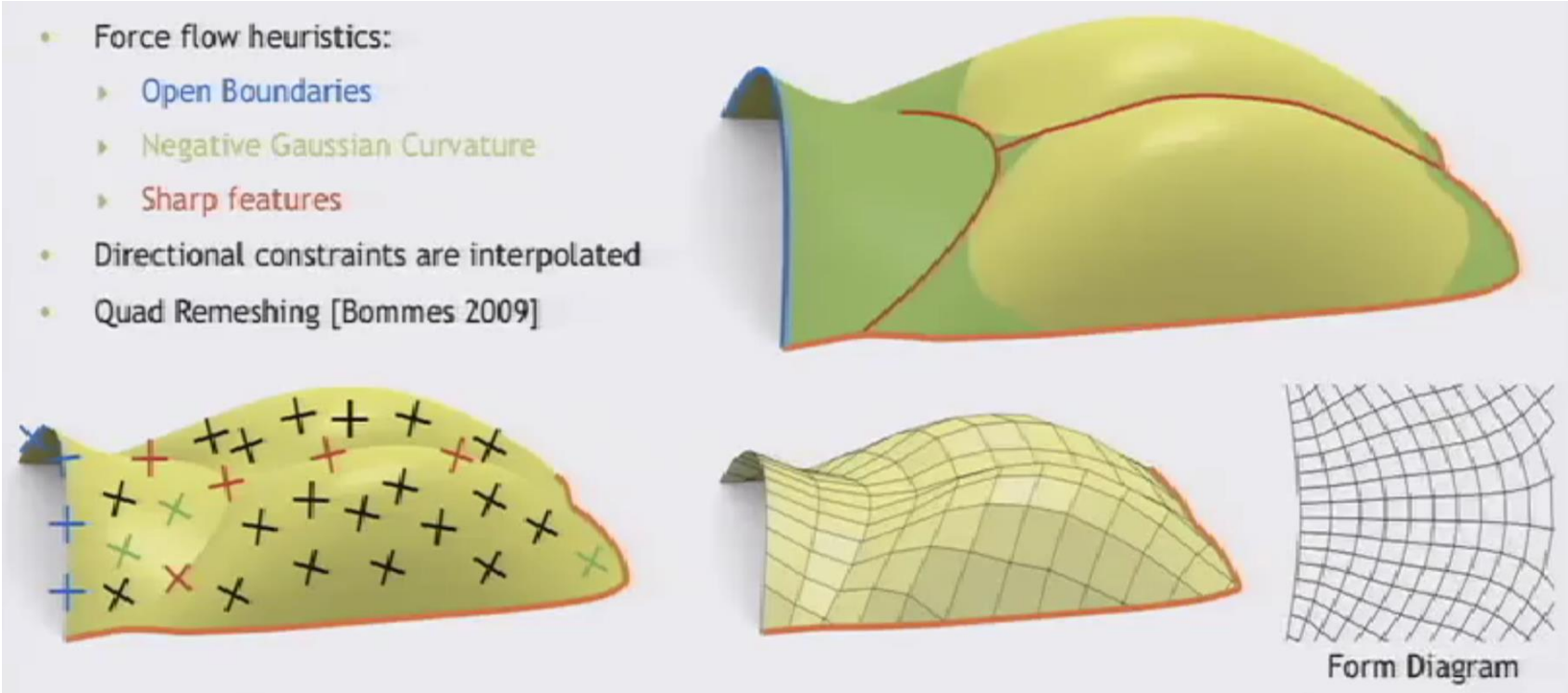


Reduced-order shape optimization using offset surfaces [2015]

Fabrication and Graphics

Geometry Processing

- Representations
- Curvature
- Vector fields

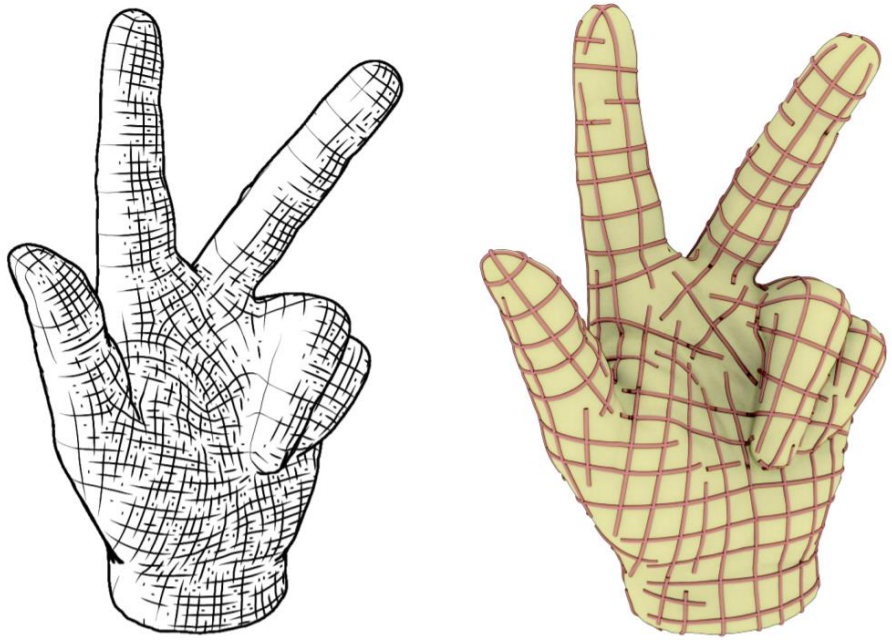


Designing unreinforced masonry models [2013]

Fabrication and Graphics

Geometry Processing

- Representations
- Curvature
- Vector fields



Field-aligned mesh joinery [2014]

Agenda

- What is additive manufacturing?
- Challenges
- **Computational fabrication and graphics?**
  - **Appearance**
  - **Physical simulation**
  - **Geometry Processing**
  - **Animation**
- Computational fabrication in graphics

Fabrication and Graphics

Animation

- Rigs
- Kinematic Chains
- Motion Capture
- Motion curves
- Motion features

Fabricating articulated characters from skinned meshes [2012]

Fabrication and Graphics

Animation

- Rigs
- Kinematic Chains
- Motion Capture
- Motion curves
- Motion features

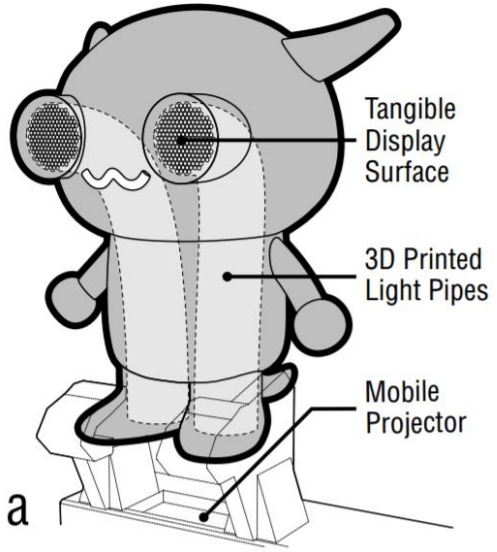
Fabricating articulated characters from skinned meshes [2012]

Agenda

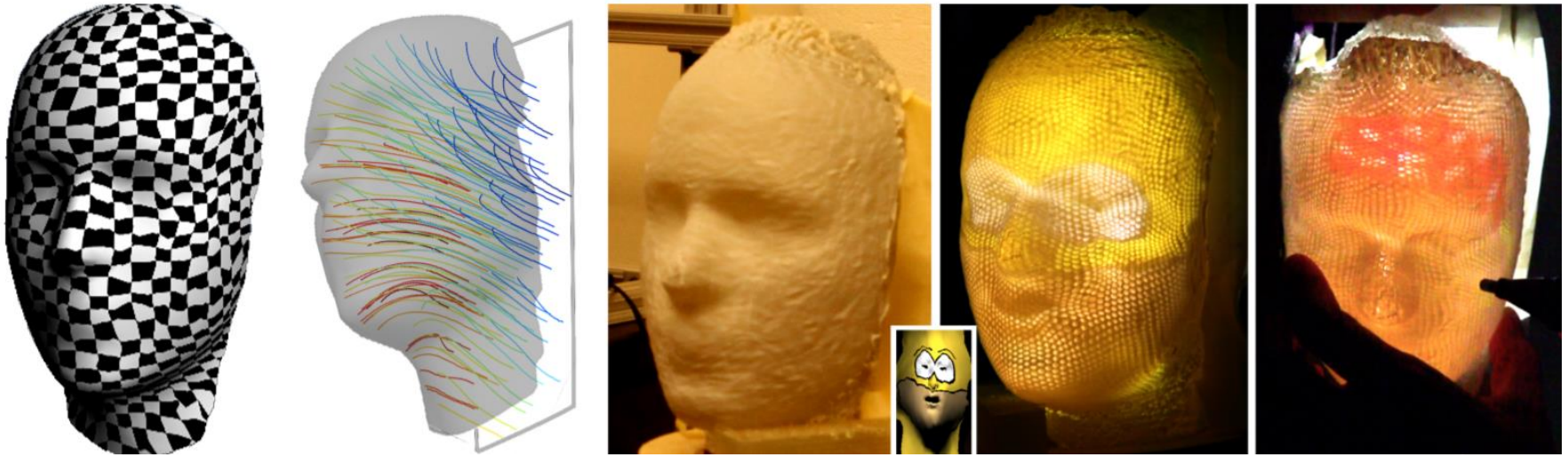
- What is additive manufacturing?
- Challenges
- Computational fabrication and graphics?
- **Computational fabrication in graphics**
  - **Appearance**
  - **Integrity and deformation**
  - **High-Level Design**
  - **Process optimization**
  - **Frame works**

Fabrication in Graphics

Appearance



Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices [2012]



Computational light routing: 3D printed fiber optics for sensing and display [2014]

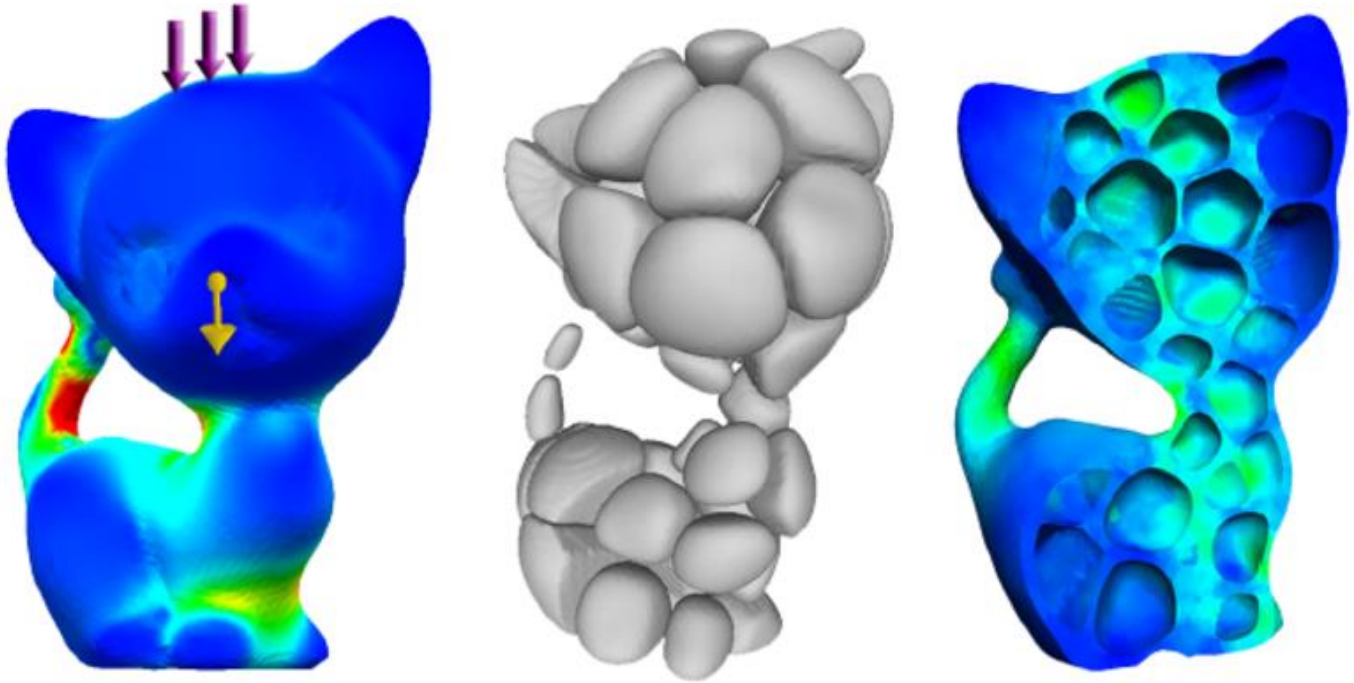
Fabrication in Graphics

Appearance

Synthesis of filigrees for digital fabrication [2016]

Fabrication in Graphics

Integrity



Build-to-last: Strength to weight 3d printed objects [2014]

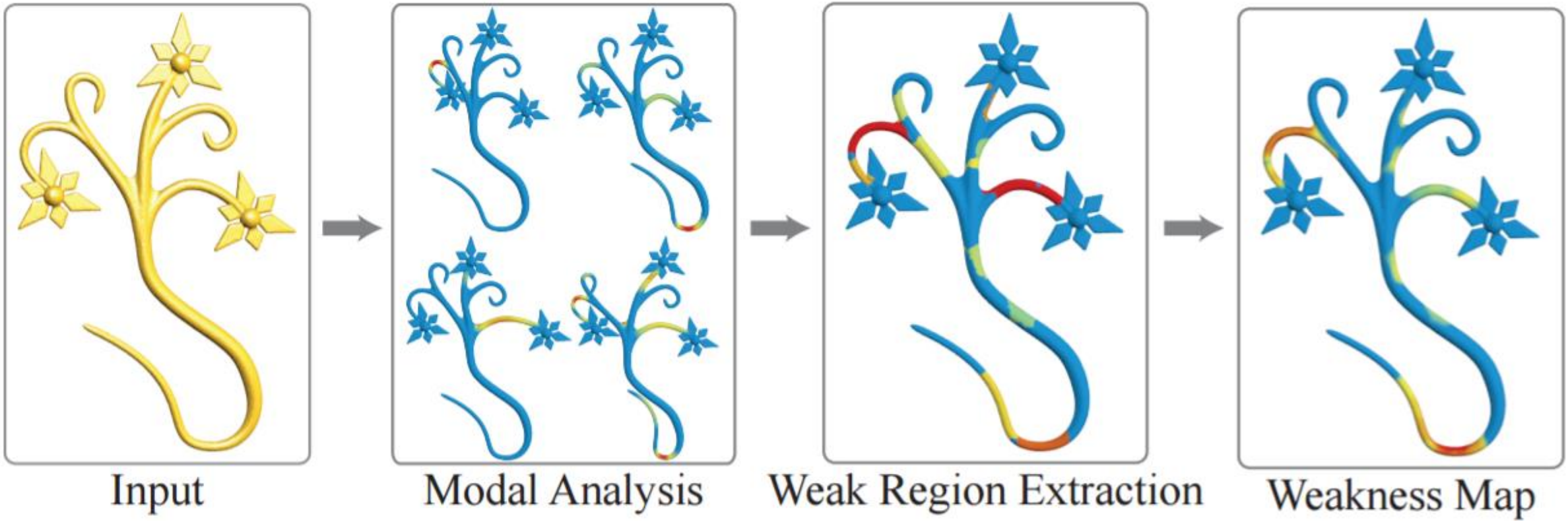
Integrity

A System for High-Resolution Topology Optimization

Jun Wu, Christian Dick, Rüdiger Westermann

Fabrication in Graphics

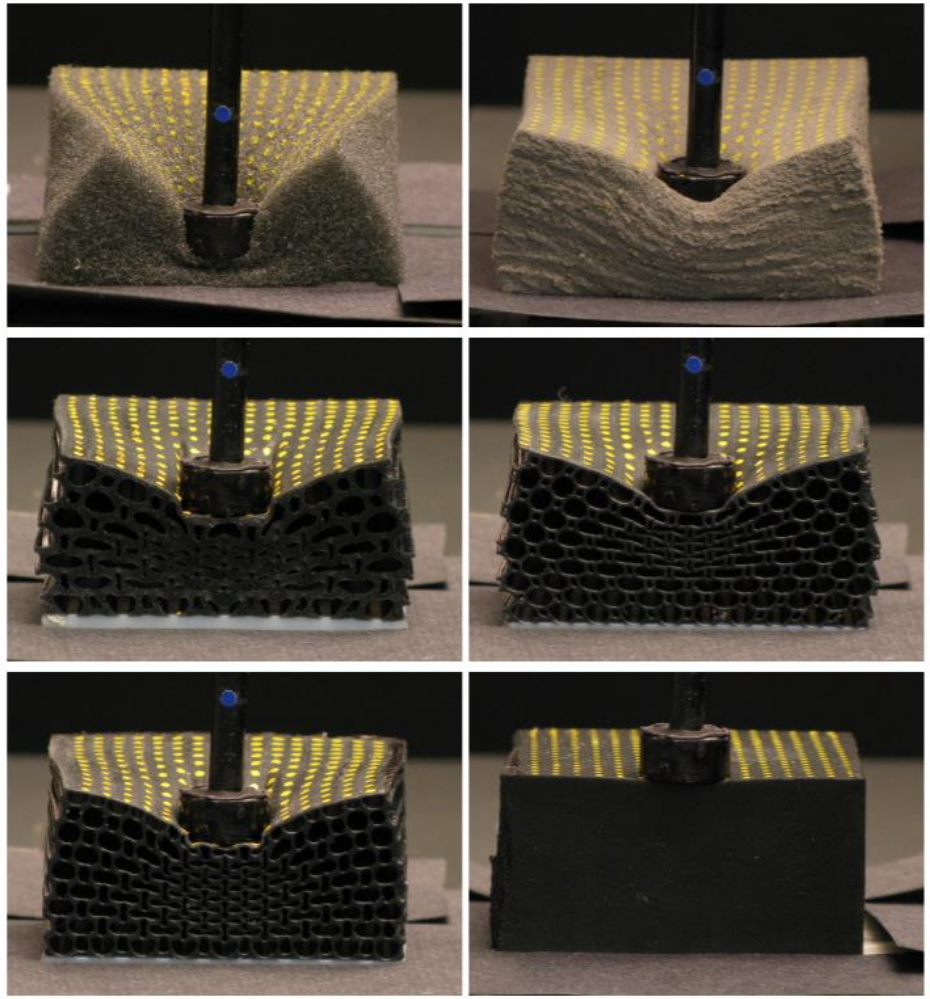
Integrity

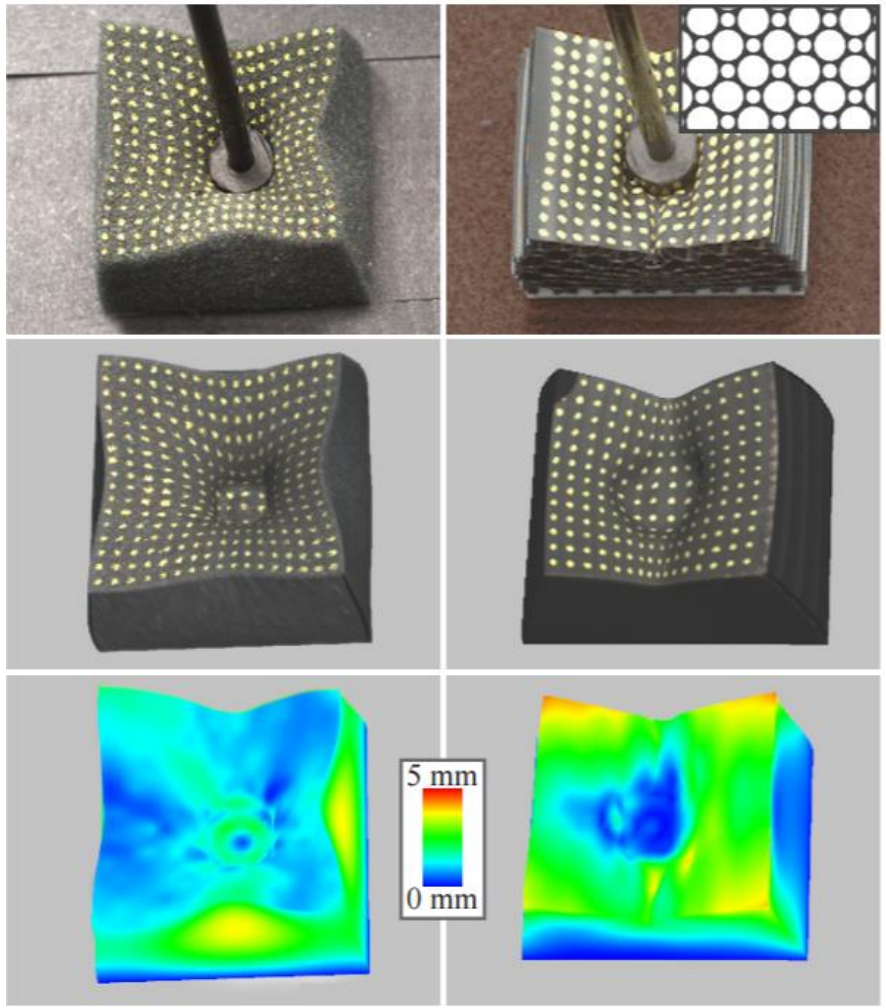


Worst-case structural analysis [2013]

Fabrication in Graphics

Deformation Behavior

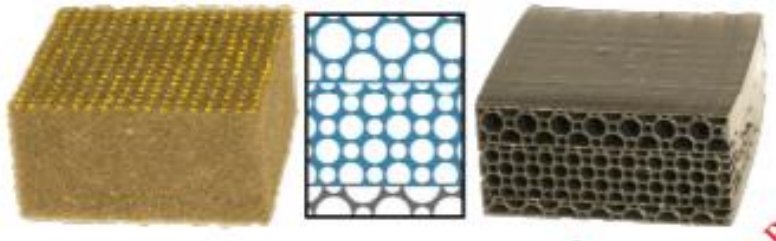


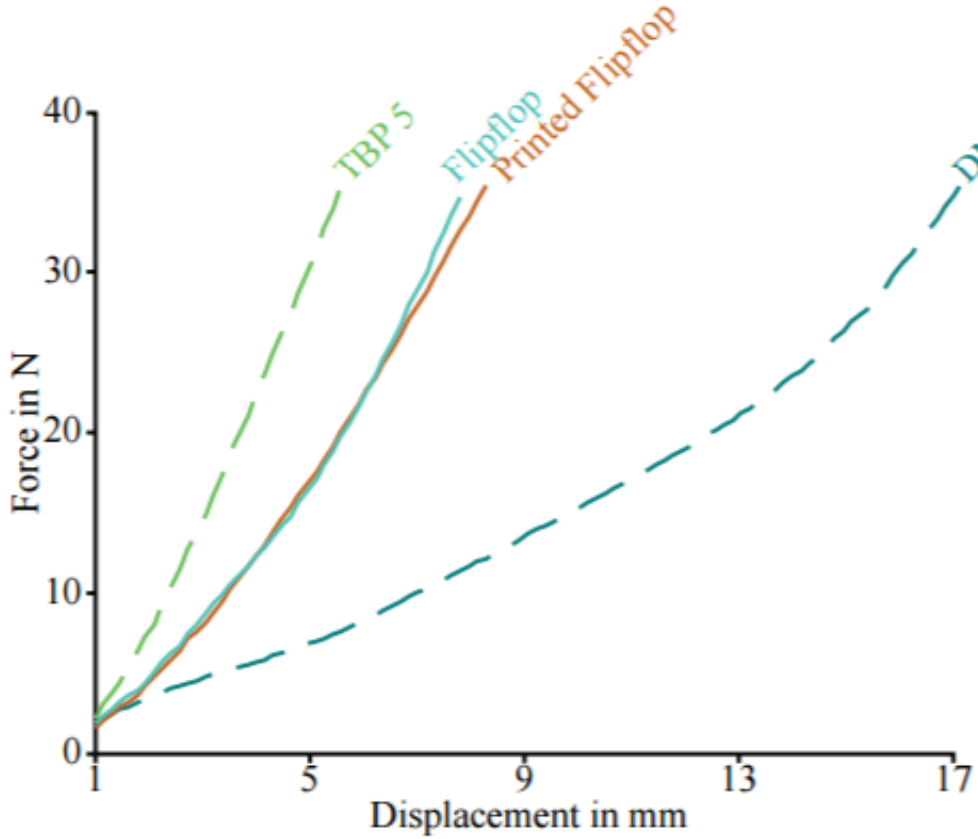


Design and fabrication of materials with desired deformation behavior [2010]

Fabrication in Graphics

Deformation Behavior



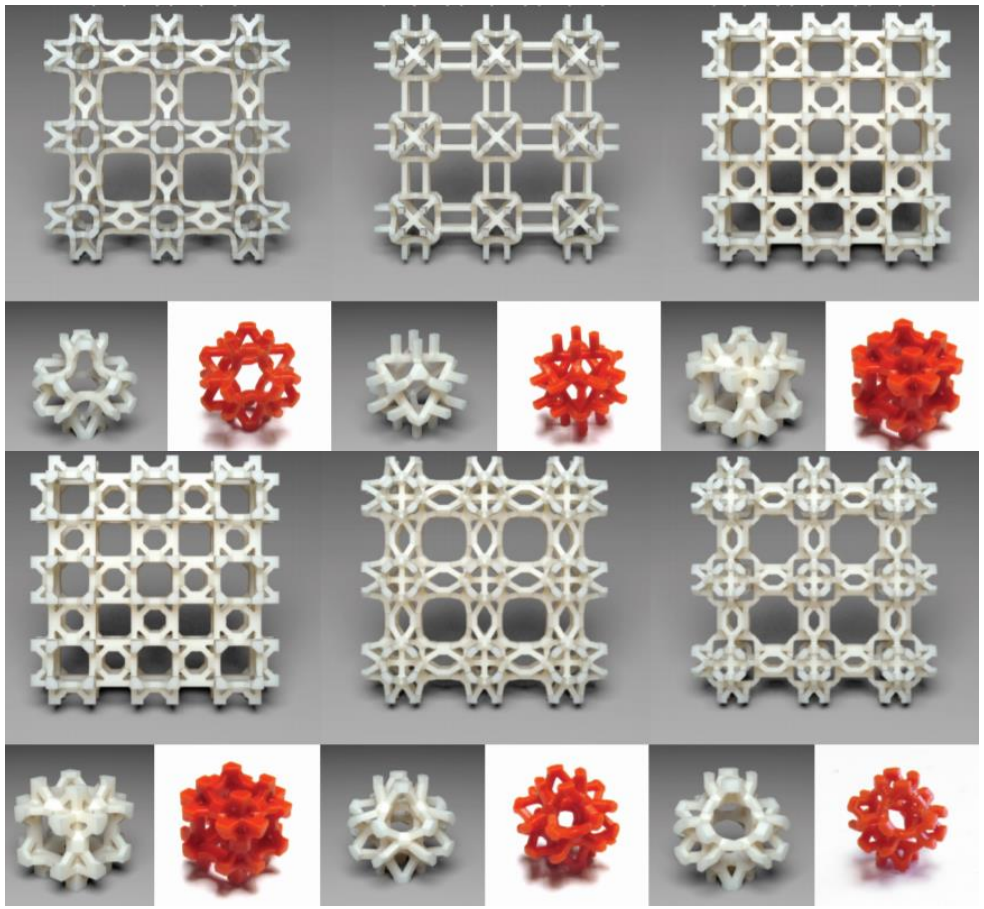


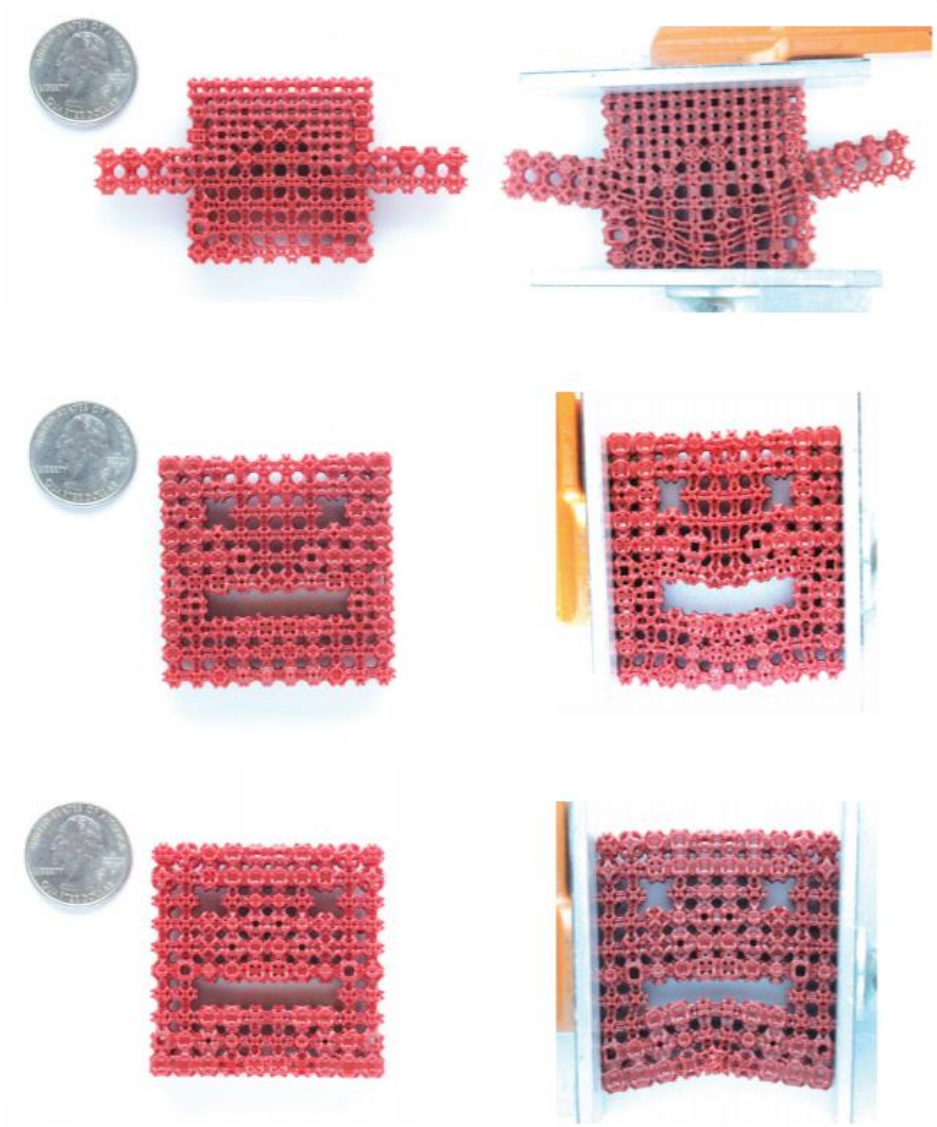
Design and fabrication of materials with desired deformation behavior [2010]

Fabrication in Graphics

Deformation Behavior

- Cellular structures





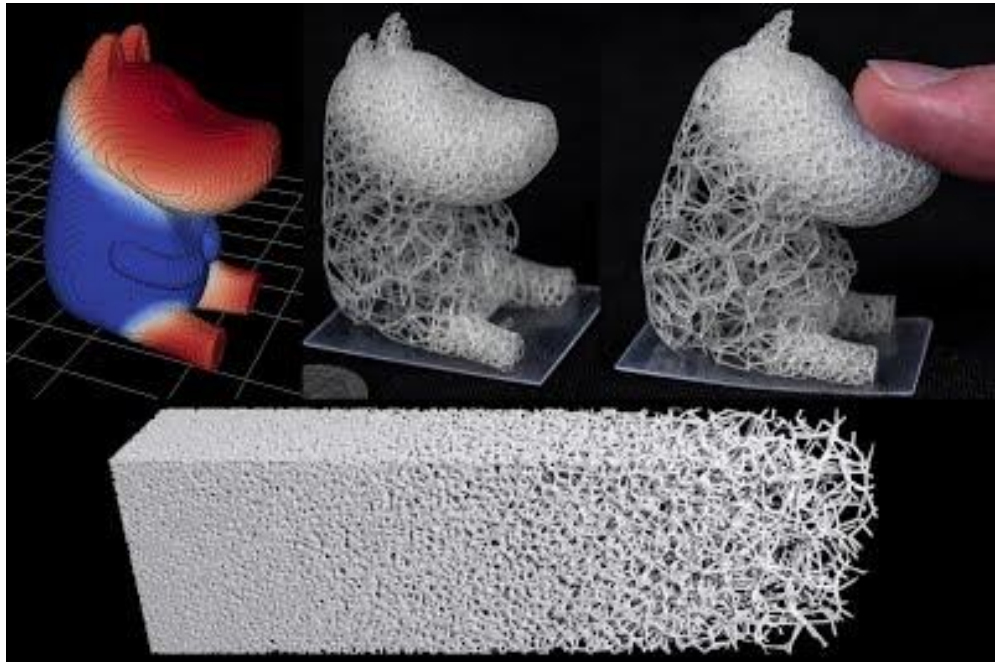
Elastic textures for additive fabrication [2015]

Fabrication in Graphics

Deformation Behavior

- Cellular structures

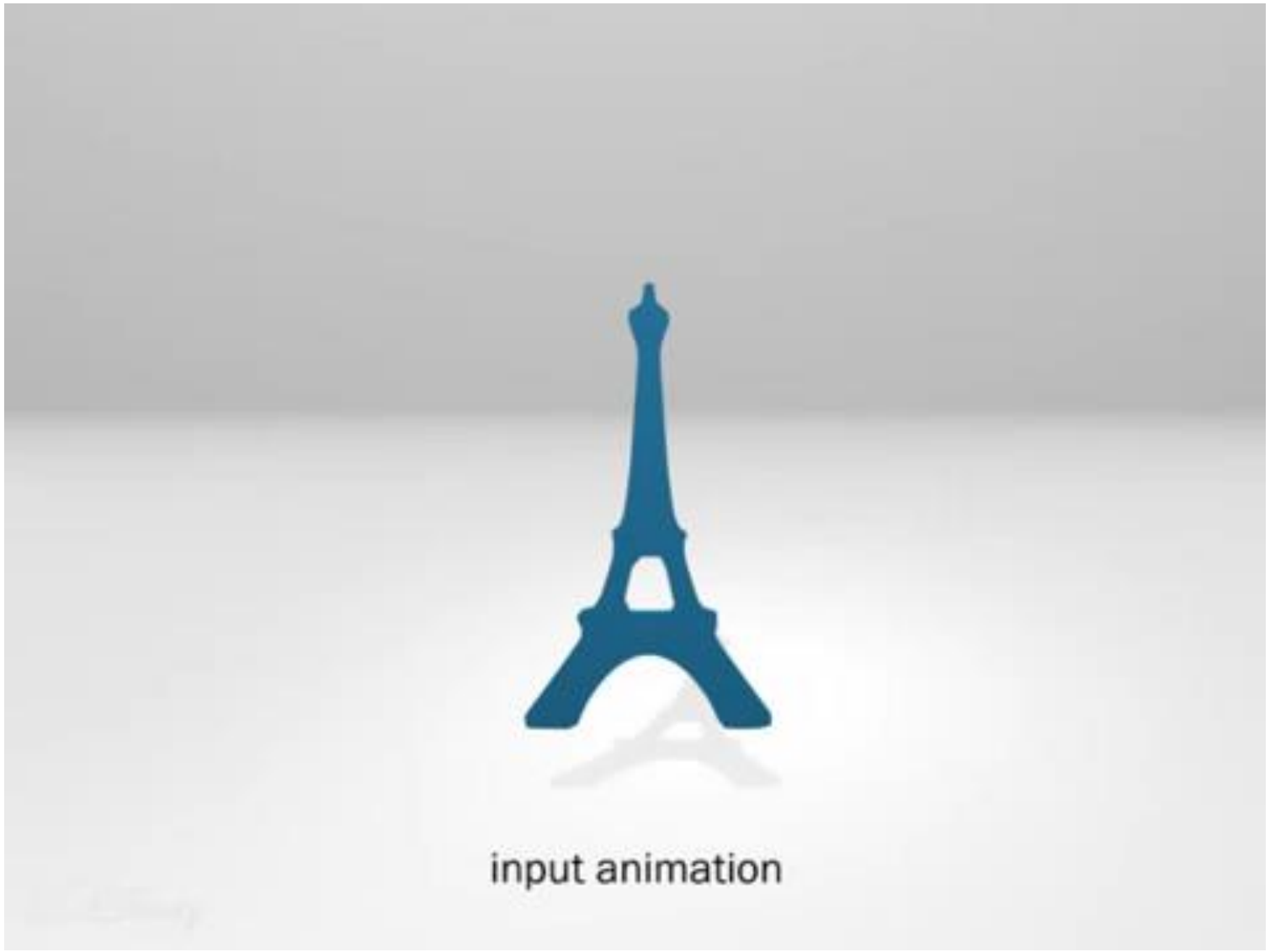
Microstructures to control elasticity in 3d printing [2015]



Procedural voronoi foams for additive manufacturing [2016]

Fabrication in Graphics

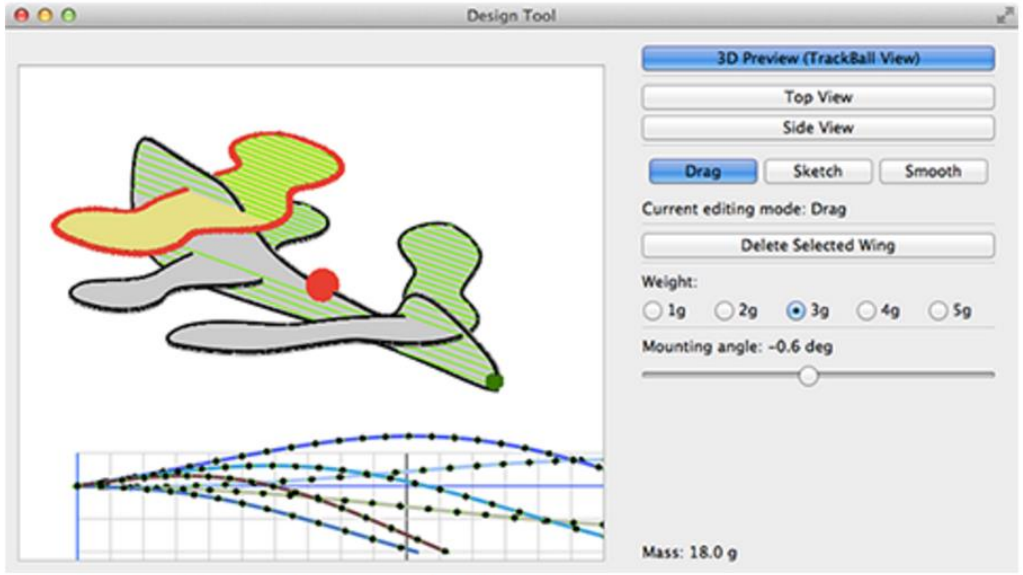
Deformation Control



Computational design of actuated deformable characters [2013]

Fabrication in Graphics

High-level design



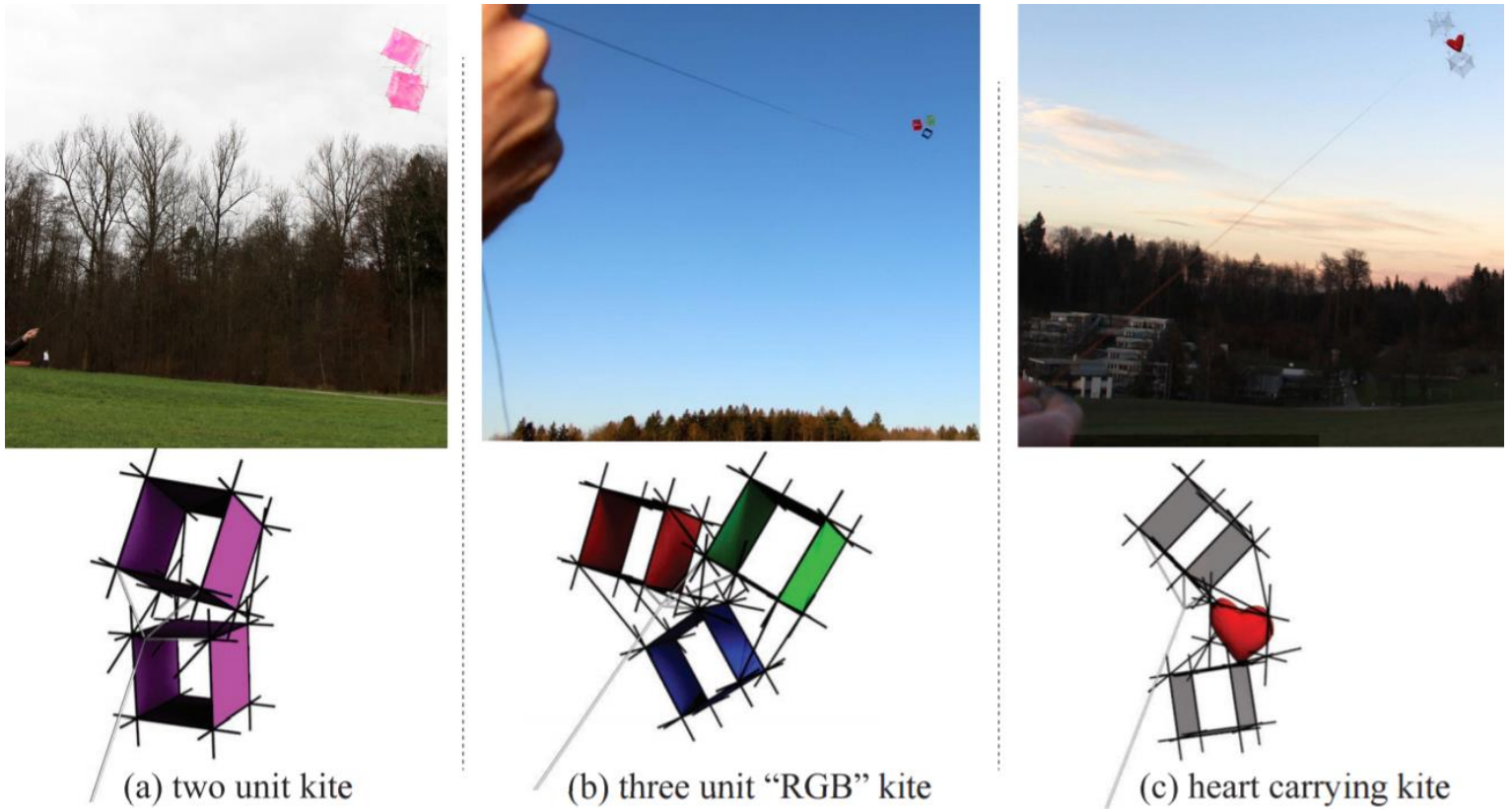
Screen capture of Pteromys design tool.

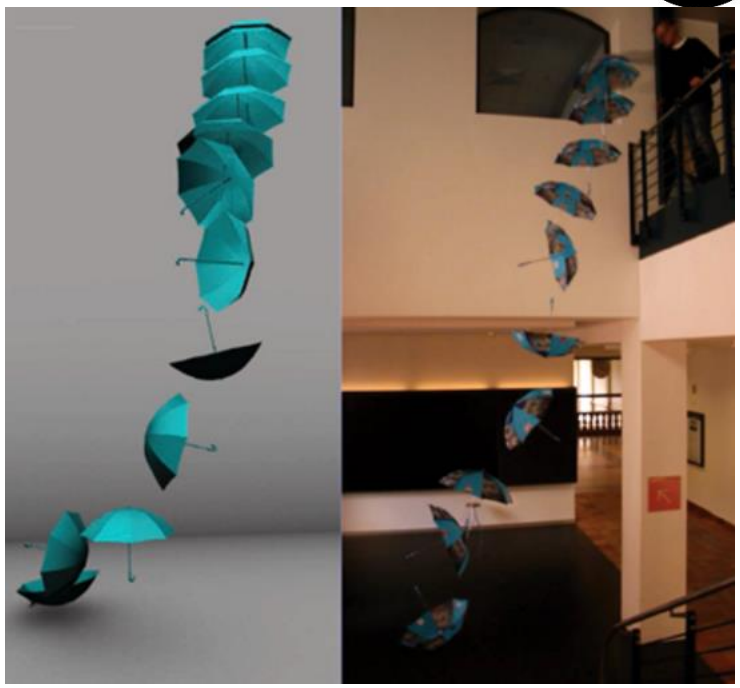
Airplanes designed by the Pteromys system.

Pteromys: Interactive design and optimization of free-formed freeflight model airplanes [2014]

Fabrication in Graphics

High-level design

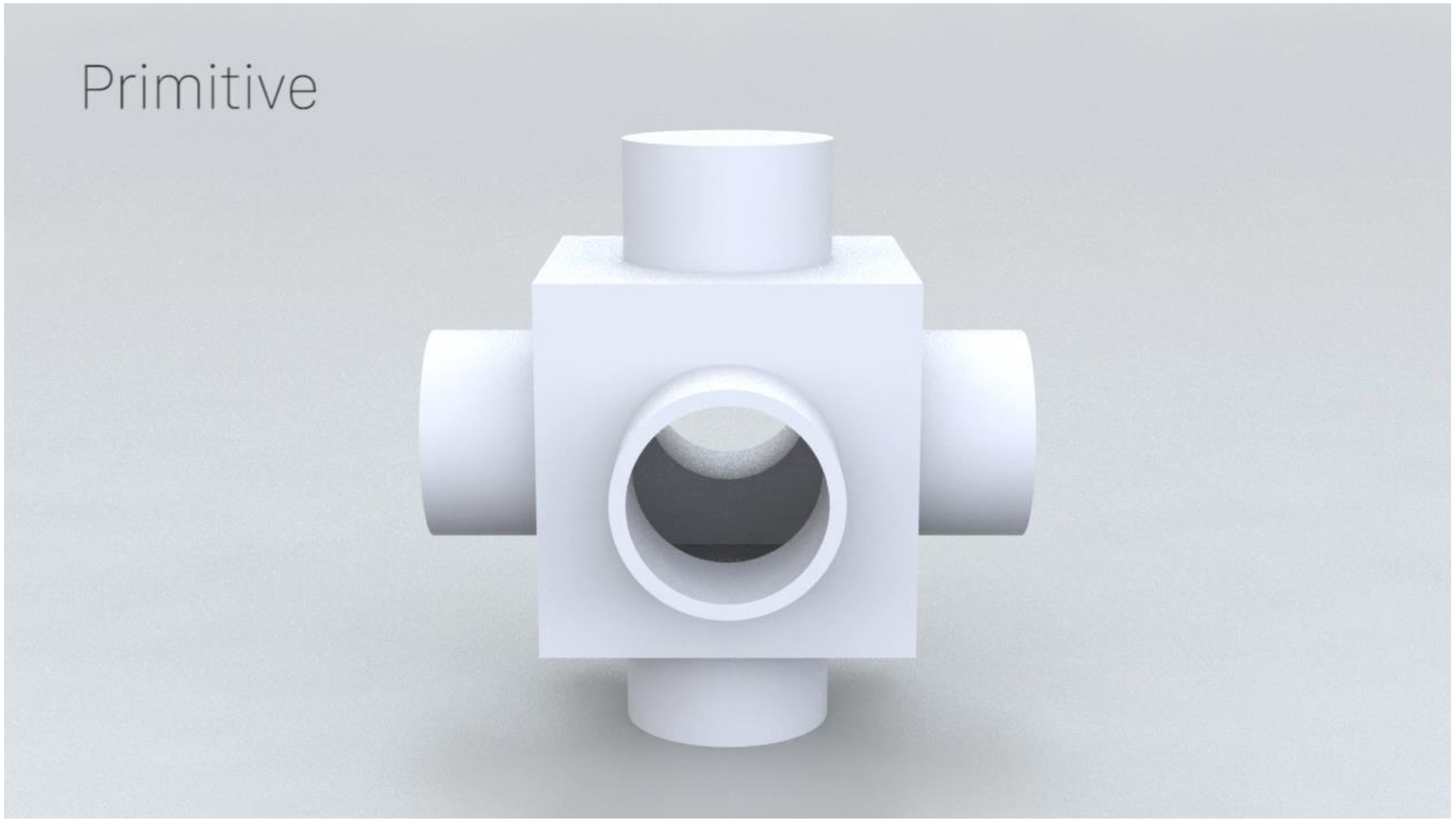




Omniad: Data-driven omni-directional aerodynamics [2015]

Fabrication in Graphics

High-level design



Acoustic voxels: Computational optimization of modular acoustic filters [2016]

Fabrication in Graphics

High-level design

Acoustic voxels: Computational optimization of modular acoustic filters [2016]

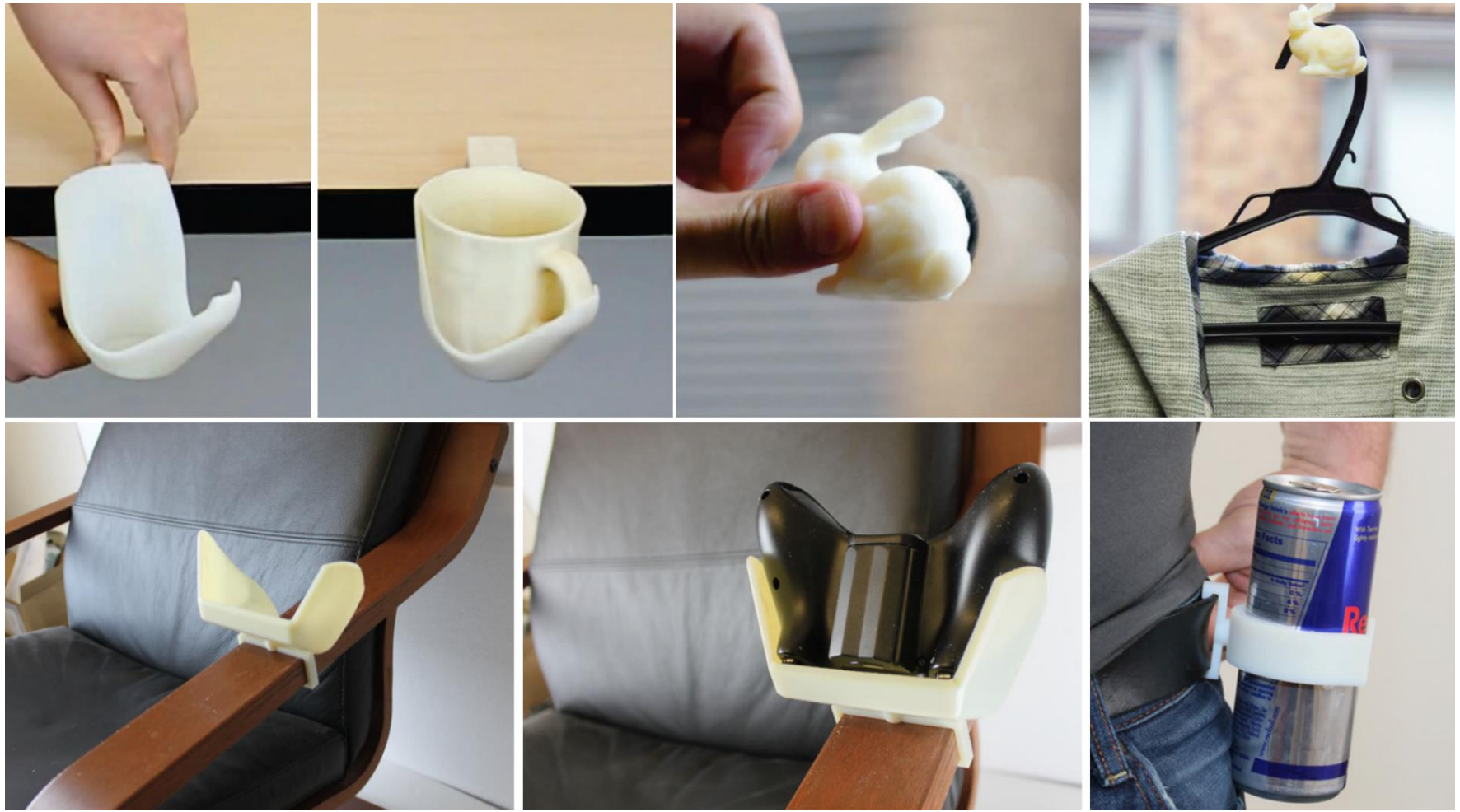
Fabrication in Graphics

High-level design

Design and fabrication by example [2014]

Fabrication in Graphics

High-level design



Autoconnect: Computational design of 3d-printable connectors [2015]

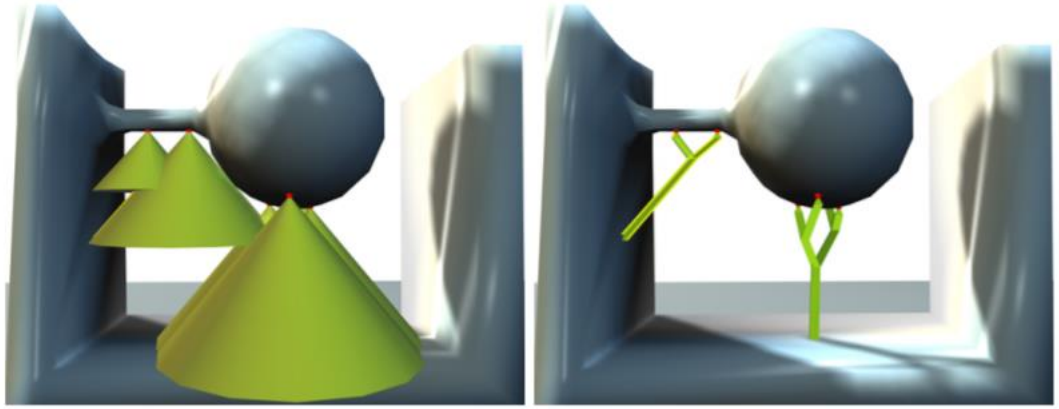
Fabrication in Graphics

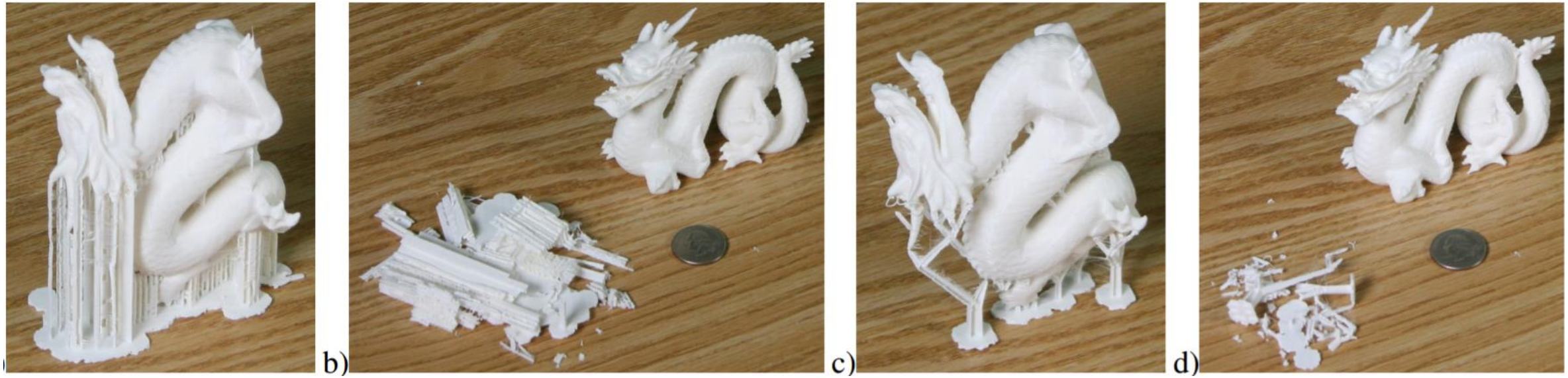
High-level design

Computational Design of Mechanical Characters [2013]

Fabrication in Graphics

Process optimization





Clever support: Efficient support structure generation for digital fabrication [2014]

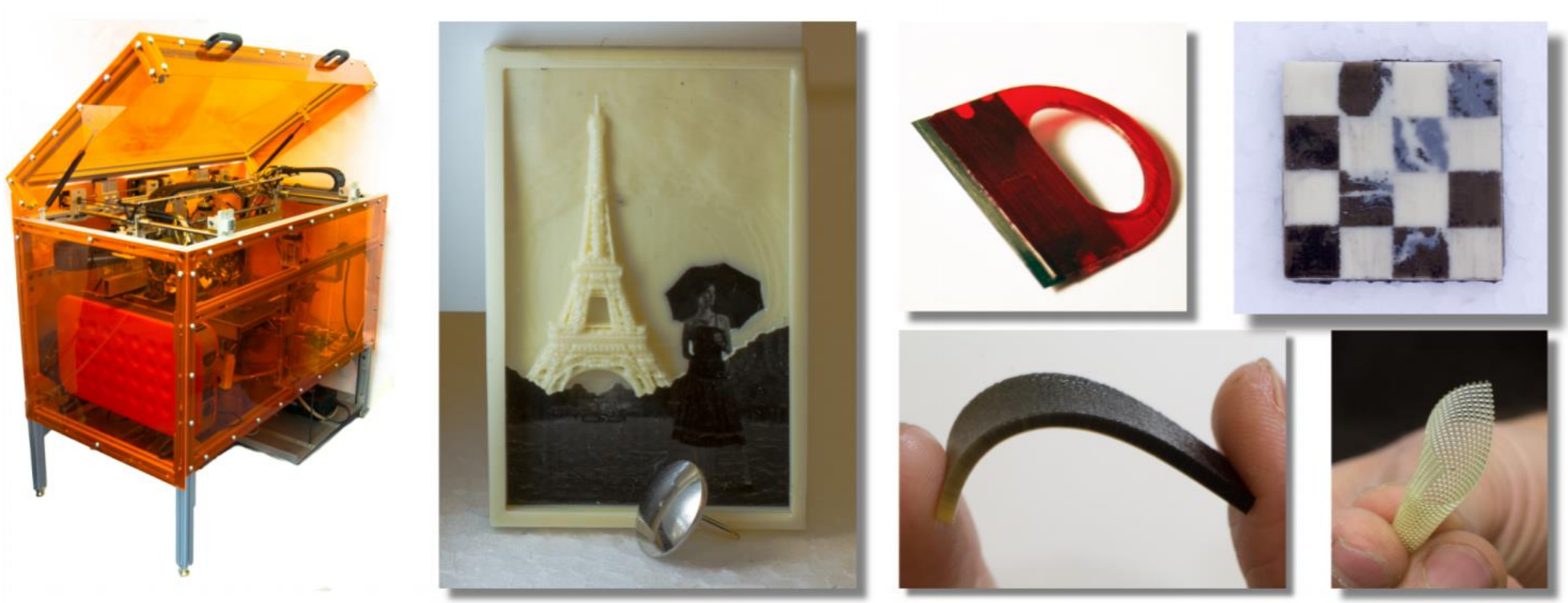
Fabrication in Graphics

Process optimization

Chopper: Partitioning models into 3D-printable parts [2012]

Fabrication in Graphics

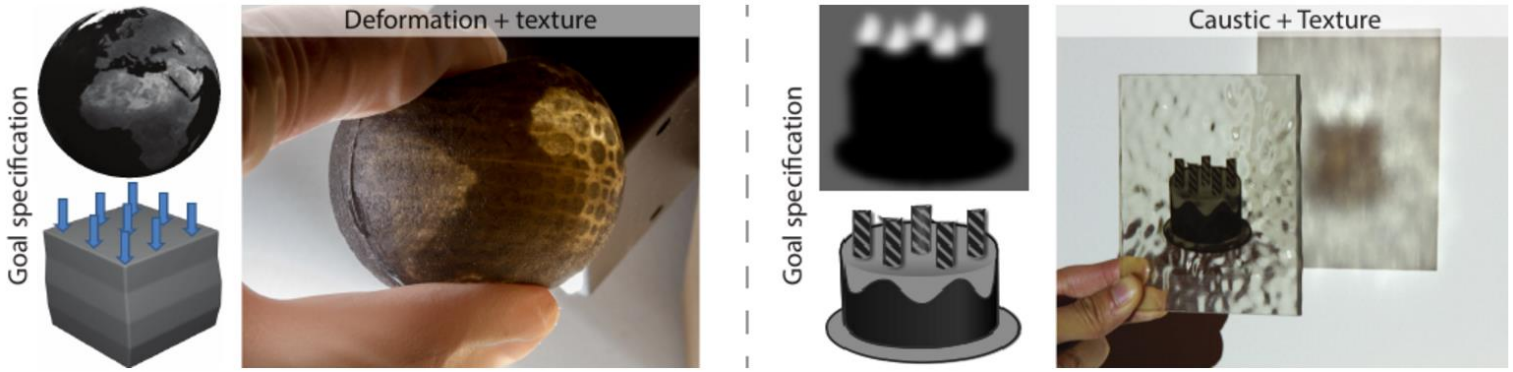
Process optimization



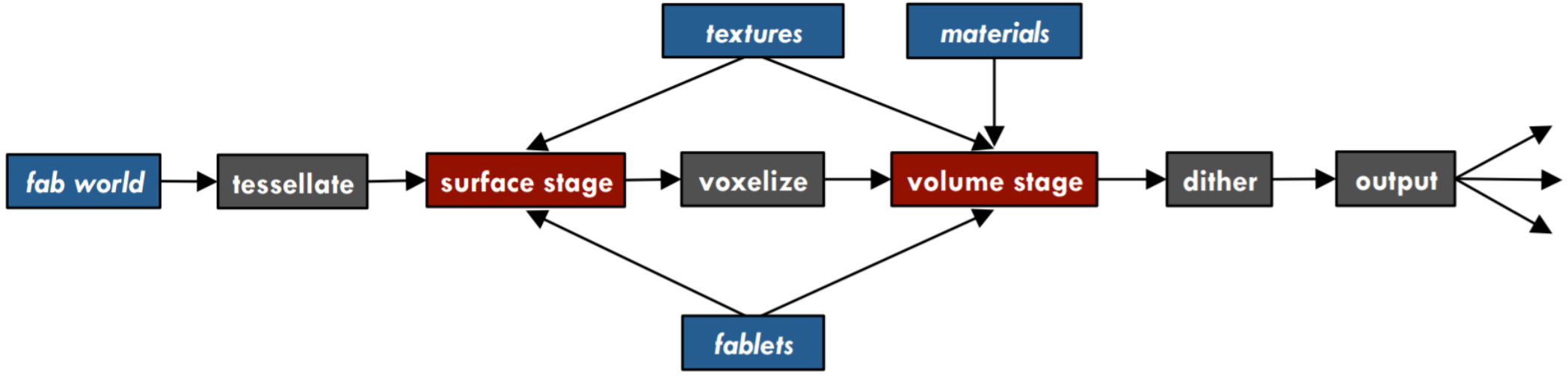
Multifab: A machine vision assisted platform for multi-material 3d printing [2015]

Fabrication in Graphics

Frameworks



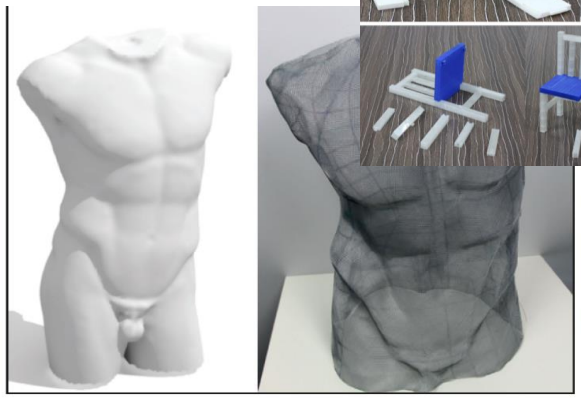
Spec2Fab: A reducer-tuner model for translating specifications to 3D prints [2013]

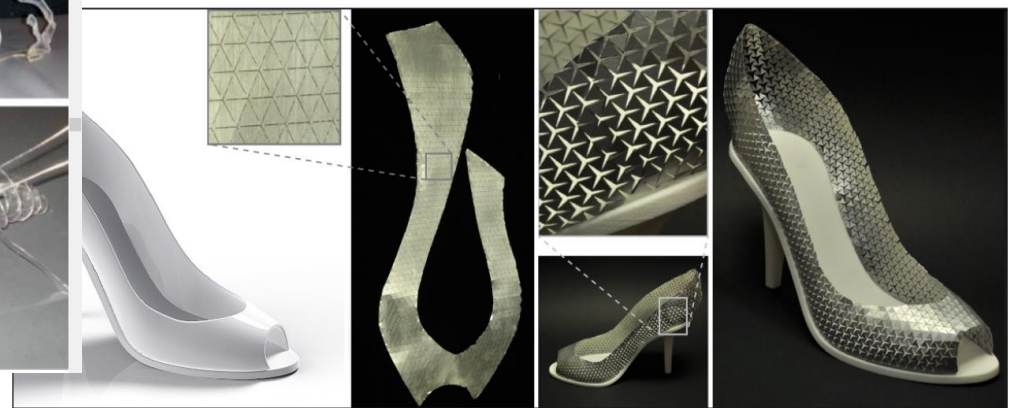


Openfab: A programmable pipeline for multi-material fabrication [2013]

Fabrication in Graphics

LOTS more





Discussion

Discussion

- Small scale, initial concept
- Separate design and manufacturing processes
- Under considered technologies
  - Metal sintering
  - Composite materials
- Large collections remain unexploited

Discussion

- A design gap
  - A fundamental change in design concepts

- Design through objectives

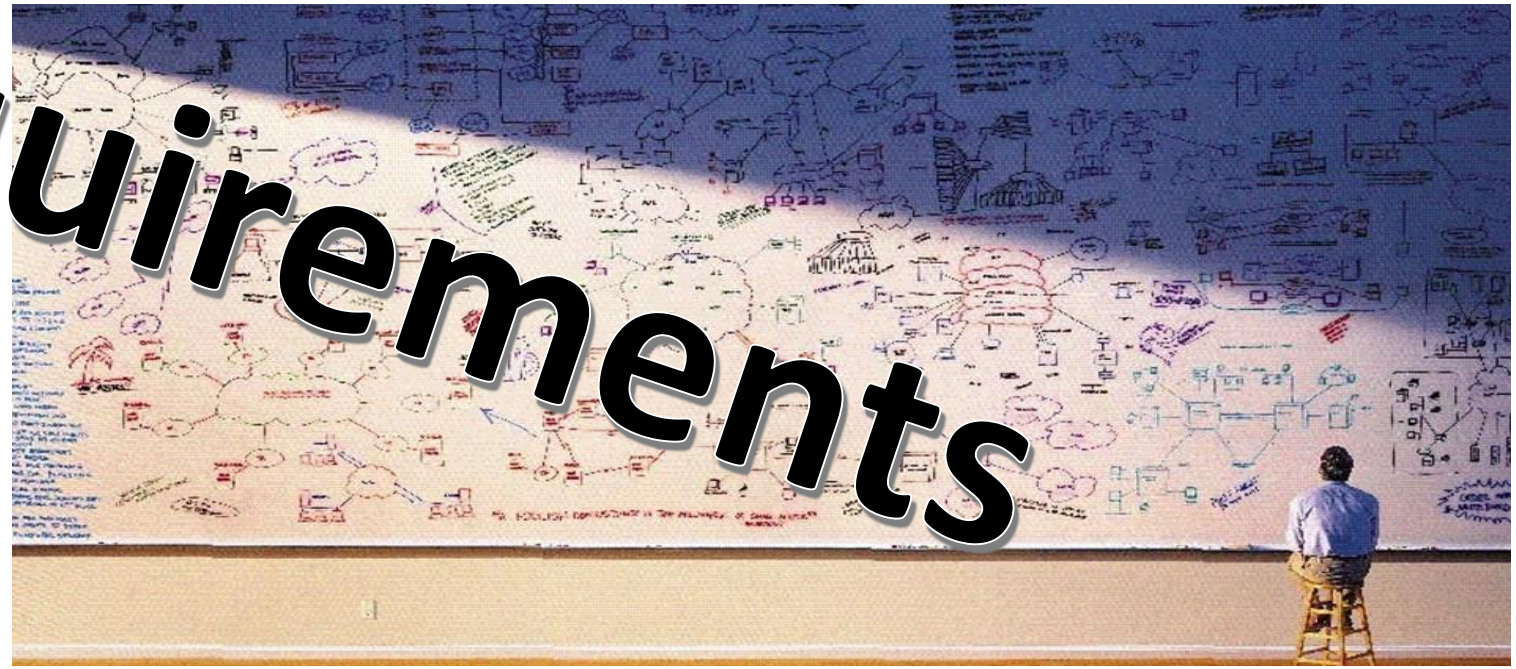
Future of Fabrication

Fabrication Research

Desig

Practical

Requirements



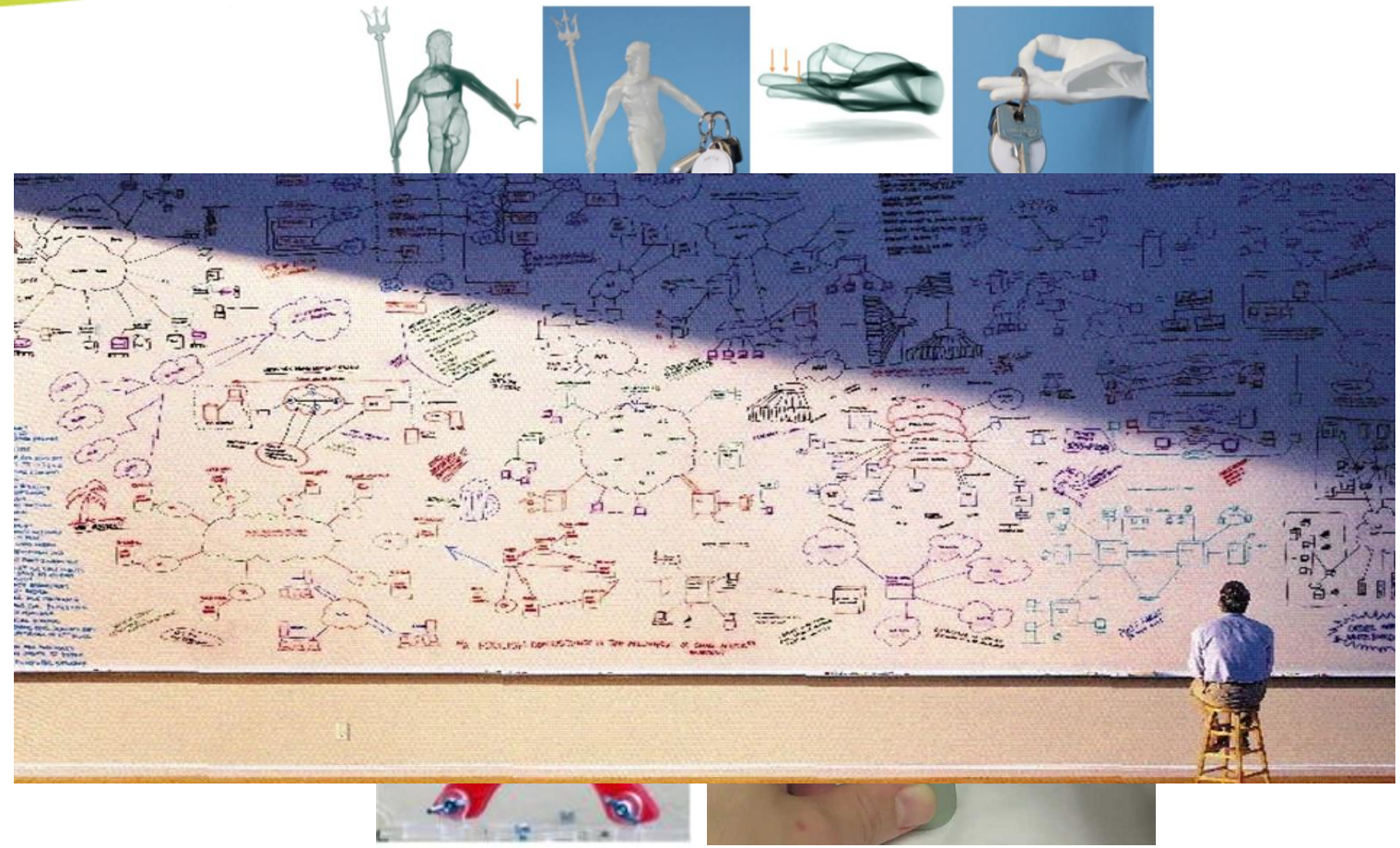
Future of Fabrication

Fabrication Research

Design

Practical

Objectives



High-res topopt, reduction, Skouras, Skinned meshes

Future of Fabrication

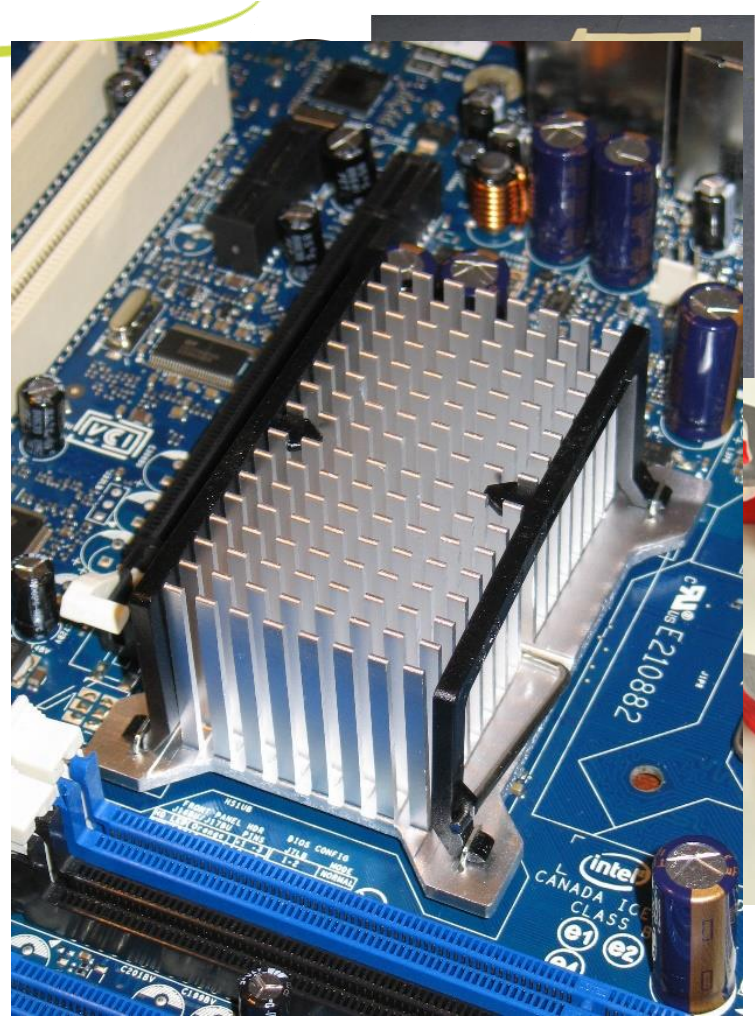
Fabrication Research

Design

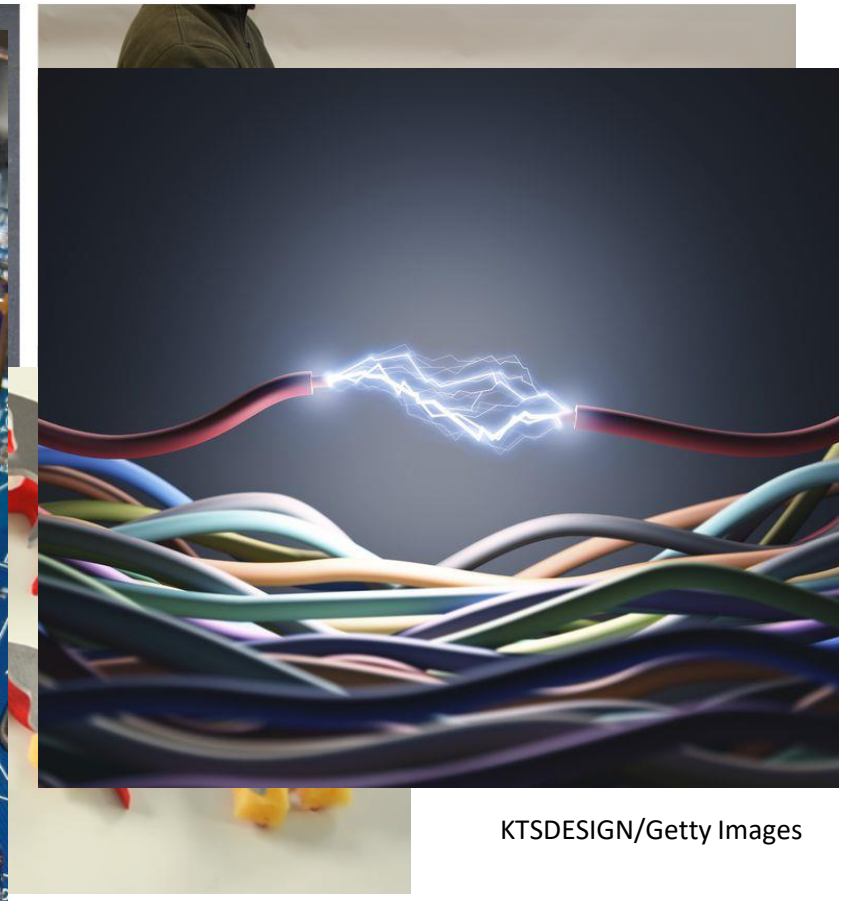
Practical

Objectives

- Types



Wikipedia



KTSDESIGN/Getty Images

[Bharaj et al. 12]

Future of Fabrication

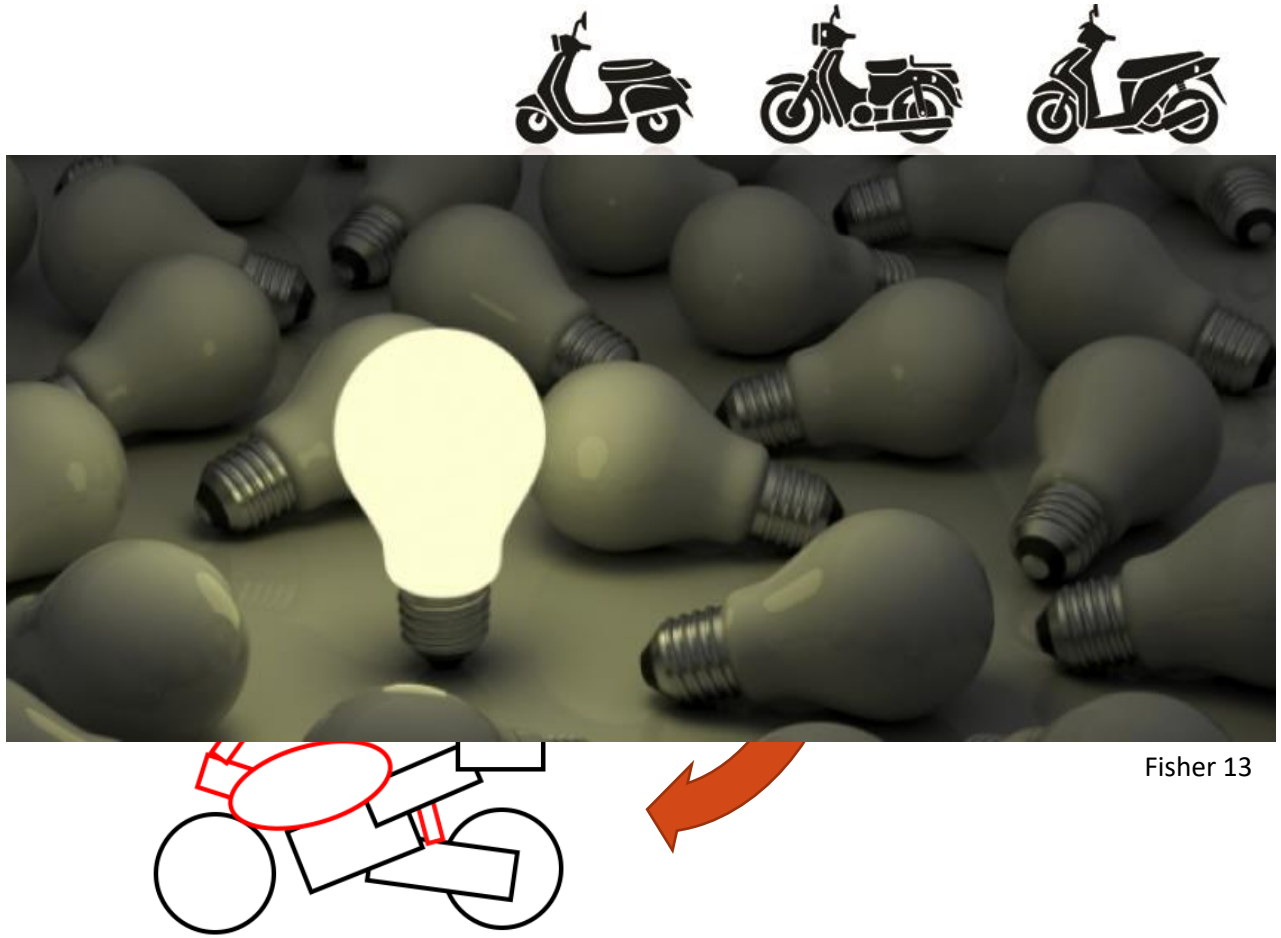
Fabrication Research

Design

Practical

Objectives

- Types
- Learn
- Balance



Fisher 13

Future of Fabrication

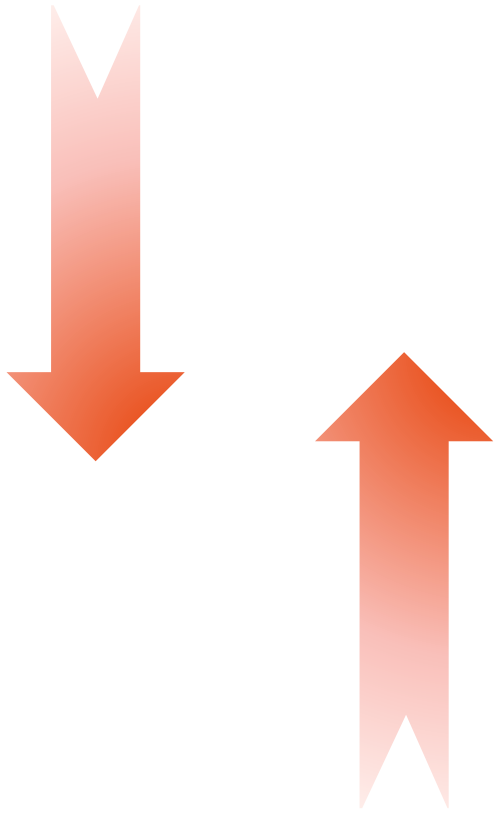
Fabrication Research

Design

Practical

Objectives

- Types
- Learn
- Balance



Representation

Future of Fabrication

Fabrication Research

M2P Marketing

Representation

Hierarchical

Abstraction

Generic

Future of Fabrication

Fabrication Research

Representation

Hierarchical

Abstraction

Generic

Informative

Thank you